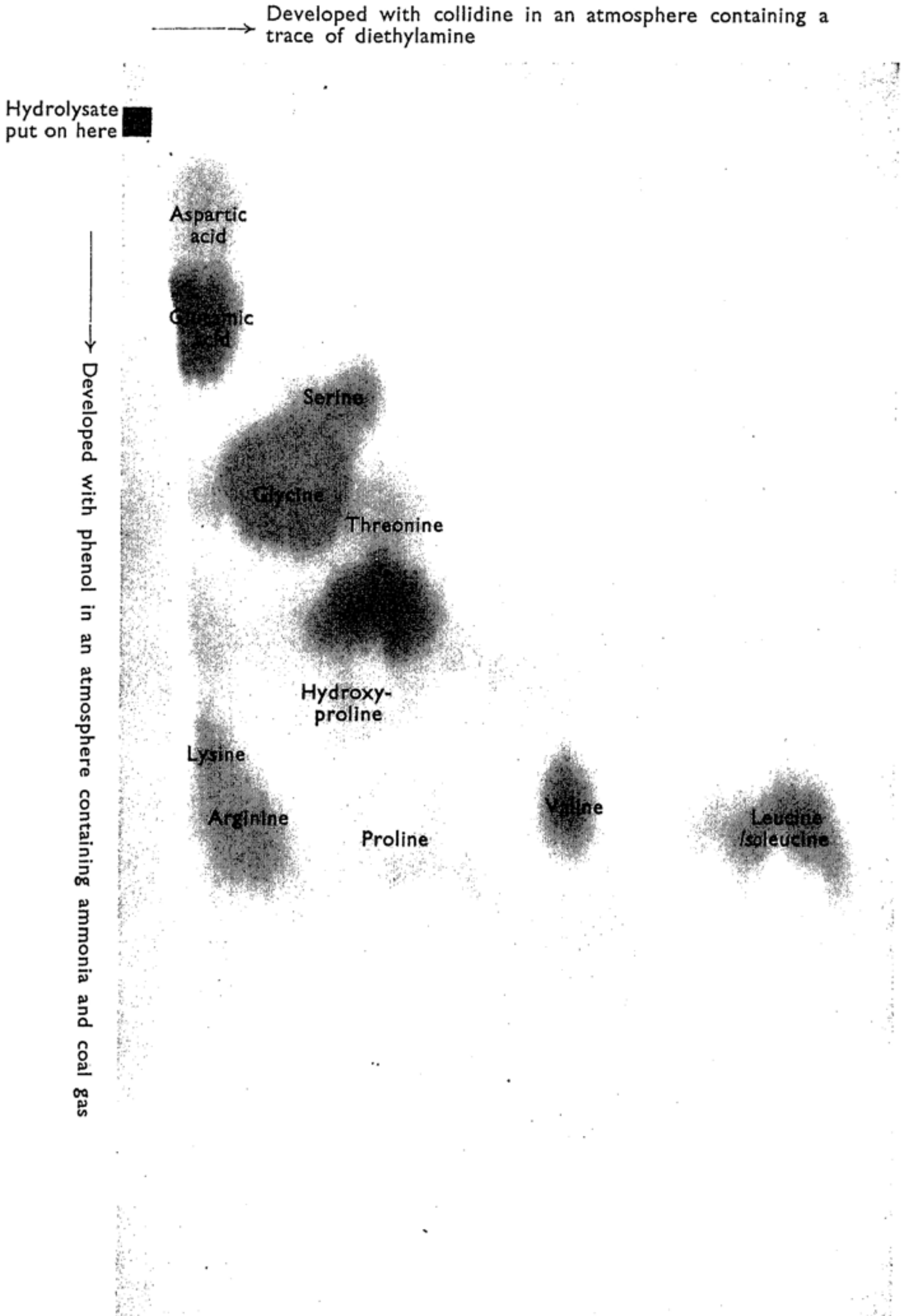
THE ORIGINS OF LIFE



A CHROMATOGRAM OF INSULIN

(*Photograph and blocks by courtesy of* Endeavour, *published by I.C.I. Ltd.*)

THE ORIGINS OF LIFE

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Sincere gratitude is expressed to those who have so generously assisted in the illustration of this book, namely, to Drs. H. Fraenkel-Conrat and R. Williams, University of California (Plate IV–ii), Dr. F. H. C. Crick, Cambridge University, and Dr. M. H. F. Wilkins, London University (Plate III), Dr. A. J. P. Martin and the Editors of *Endeavour* (Frontispiece), and Messrs. Catalin Ltd., (for loan of the molecular models depicted in Plate II.)

Preface

THIS lucidly written and stimulating book deals with two main themes, (*a*) how life probably arose and evolved on this earth, and (*b*) how it might be copied experimentally. It also sketches on a much larger canvas than before a new way of looking at things brought into the public eye in recent years by work on the so-called electronic brains and on automatic control as seen in industrial automation.

In a dramatic introduction Ducrocq takes us back to the very dawn of life itself, and exhibits the early geological and biological panorama of this planet so vividly that we are made to view it as though from a " seat in the circle ".

As a background to his more biological discussions Ducrocq outlines the nature of the processes involved in the control mechanisms used in present-day engineering processes. An interesting account is given of the automatic factory in which such devices are largely used, and they are compared with the complex system of controls exercised by the living creature. He also gives us a fascinating insight into the factory of the future which would have the capacity of automatically improving upon its products. We are then introduced to the new and highly significant researches in the biochemistry of life, which, though exciting chemists and biologists today, are not as well known as they should be to the non-specialist. Ducrocq next shows in a striking fashion how work in the field of computing machines might help us to understand the way living creatures reproduce their like. Finally, he sketches man's place in the universe, emphasising that it is man's capacity for abstract thought, language and tool-making which enables him to transcend organic evolution.

This cogent piece of argument has its root in various soils—in

recent developments in logic, computing theory, communication engineering, physics and biochemistry. It is a serious attempt to synthesise these disciplines into a new world picture and at the same time to throw light on that intriguing mystery—the origin of life. In a discussion of this subject (*New Biology*, No. 16, 1954) J. B. S. Haldane examined the hypothesis that life originated as a result of an event, which, however improbable, was almost certain to happen, given sufficient time, from ordinary chemical reactions. He also argued that this hypothesis should be taken seriously, since the theory of instructions to machines is being rapidly developed in connection with electronic computers. One can, for example, impress on a punched tape instructions to make these machines perform complex calculations or control the production of an automatic factory.

Haldane next asked whether it would be possible to give a machine an instruction to make another like itself also provided with a copy of these instructions. If this should prove to be the case, such a machine would then have some claim to being alive. J. von Neumann, who developed a logic of self-reproducing machines, believed this was possible and that such a machine would go on reproducing itself as long as the parts needed for this purpose were available. As a geneticist Haldane further suggested that the biochemistry of long chain molecules which reproduce themselves is probably a clue to a full understanding of genetics. In recent years work on the structure of deoxyribonucleic acid, or DNA as it is called for short, by F. H. C. Crick and the American scientist J. D. Watson, seems to show that this substance contained in the chromosomes not only duplicates itself, but also controls the development of the rest of the cell in a specific way.

The notion of a self-reproducing machine, which seems first to have been put forward by von Neumann after a theorem of A. M. Turing, has been also taken over by Ducrocq and amplified into an hypothesis as to the origin of life, which he closely ties up with current developments in the field of cybernetics and automation. Ducrocq claims that cybernetics, with its interest in control mechanisms, bridges the gap between biological and physical systems. Cybernetics, or the science of control and communication in animal and machine, thus becomes extended under the heading of "biocybernetics" to explain the very nature of life

itself. Whereas physical systems usually show a tendency to entropy, to run down, biological systems tend to organise themselves on to a higher level, taking in raw material from their environment and using it to repair and reproduce themselves. Engineers have now constructed machines which, like living organisms, are by relay systems (servo-mechanical devices) able to control their internal organisation. An early but notable example is to be seen in the so-called Saxony spinning-wheel invented by a German wood-carver in the sixteenth century still used today in the Hebrides, upon which modern machine spinning is based. This enables both the spinning and winding of the thread to be performed simultaneously. The large wheel turned by the foot treadle operates through a single cord, by which it drives two separate tools, the spindle which inserts the twist in the thread, and the flyer which winds the thread on the bobbin. The flyer and bobbin, as a result of the differential friction of their respective pulleys, travel at different speeds so as to keep the twisting and winding in step, no matter whether the speed of the wheel's working is increased or decreased. Today we have thermostatic controls, speed regulators, automatic pilots, as well as electronic tortoises which will react to flashing lights and return to their hutches for a feed!

A feature of such devices (or relay systems) is that they usually consist of two closely linked systems, so that a trifling amount of energy exerted by one, say in the form of a signal, will release a much larger amount of energy from the other, which is roughly what is meant when one speaks of a relay system.

A very simple example of this is when we press a bell-push and the bell rings. This control, as with the spinning-wheel, may also operate automatically. Consider, for example, the case of the ordinary thermostatic control of an electric iron, which switches off automatically when the temperature rises above a certain level, and switches on again when it falls below that level. Or take the error-correcting mechanisms, as seen in the early radar-controlled anti-aircraft fire, which after successive approximations resulting from " fed back " error signals finally enable the gun to hit its target. Such mechanisms have been termed goal-aiming, since they tend to simulate the behaviour of animals when actuated by goal-seeking tendencies—such as hunger or sex.

Living creatures exhibit all the features of control or " negative

feed-back systems " as they are sometimes called, in which when the output deviates from a required level, or is in error with respect to it, the fed-back signal indicating the deviation causes the mechanism to compensate for the error, correcting the output. In a similar manner the organism attempts to reach a state of equilibrium with its environment. Our motor nerves by means of messages sent to the brain enable us, for example, to control our arm and hand muscles in such a way that we can correct any errors which might occur when we handle things.

That this process is going on without our ordinarily noticing it is shown when these controls do not function properly, as in Parkinson's disease, an ailment of the nervous system where the patient has great difficulty in handling objects. He persistently overcompensates; in performing an action, he extends himself too much, then seeing what is happening checks it and tries again, but still overshoots the mark. This is apt to set up a violent interchange of conflicting muscle workings which shows itself in a pronounced palsy. Our bodies also contain large numbers of internal control mechanisms for the regulation of blood pressure, respiratory rate, blood sugar content, body temperature, etc. The internal control (homeostasis) is directed so as to keep every aspect of our internal environment in a state of proper functioning.

Living creatures are then able to exercise both internal and external controls just as do the servo-mechanisms used by the modern engineer to control industrial plant. In both the automatic factory and in living organisms we find control mechanisms hierarchically arranged to form the complex organisation of the factory or living creatures. But there are certain important differences; industrial servo-mechanisms are large-scale in character and physical in nature, while biological controls are mainly chemical and microscopic in scale. Further, the simplest living thing is infinitely more complex than any existing factory.

Ducrocq imagines a motor-car factory in which the products are not only made automatically, but the models produced also undergo a process of evolution. An existing motor-car factory could be equipped with an intricate though compendious index system which automatically recorded what has happened to all the cars put on the road in the previous year, and would subject them to some sort of sifting operation. For example, wheel-wobble would

be checked against known causes: tyre pressures, toe-in of wheels, etc. It would also at the same time gather all possible information of new technical advances. This information could then be fed into digital computors, which would work out the specification of the new models and the necessary instructions for retooling the factory. Ducrocq contends that the evolutionary character of life could be matched by this sort of factory.

He now tries to show how organic material and the process of self-reproduction may have originated in Nature. The amino-acids from which the proteins of the living creature are constructed could have arisen in certain favourable circumstances as a result of an electrical discharge passed through a mixture of hydrogen, methane and ammonia—gases which may have formed the earth's earliest atmosphere. After successive elaborations of the fundamental organic substances, especially those forming the long chain molecules of protein and nucleic acids, elementary self-reproducing organisms would appear. The first stage of life could have been a virus-like creature. Present-day viruses have for some time puzzled biologists and chemists, because they appear to behave like chemical substances, forming regular crystals just as do non-living molecules, and yet in a suitable environment they have the power of self-duplication of living systems. Although the viruses known today cannot reproduce themselves without the assistance of a more complex living system, it seems not impossible that the precursors of present-day living creatures could have maintained themselves in the heavily salted warm thin " soup " which formed the primeval oceans, since from the very nature of the situation there could have been no micro-organisms to break down the nutritious components of the brew.

As we have already seen, the basic reproductive material in the cell chromosomes which form the genetic material of living creatures is closely bound up with the self-duplicating power of the cell. The molecule of DNA is very large and consists of a great number of smaller molecules, the nucleotides, linked together. X-ray analysis and other experiments are consistent with the view that DNA has the structure of two closely linked adjacent helices—like twin spiral springs. The nucleotides in one helix are paired with those in the adjacent one. Since there are four kinds of nucleotides pairing can take place in twenty-four

possible ways. Actually out of these only two different kinds of pairs are thought to occur, and it is tempting to suppose as Ducrocq does that this may form the basis of a 1, 0 arithmetic or a binary language. Such a language, when we deal with logical information, consists in coding quite complex expressions into a series of Yes or No answers. Crick has suggested that if we imagine the pairs of bases (or nucleotides) as corresponding to the dots and dashes of the Morse code, there is enough DNA in a single cell of the human body to encode about 1,000 large textbooks. Ducrocq therefore believes that the genes of the living creature contain in this way a set of instructions or a programme of development which might be pictured as written in terms of such a binary arithmetic. On this view a gene could be represented as a mathematical scheme embodying a large number of coefficients, in terms of which the programme of the living creature is formulated. This presumably will include instructions for the nature of the substances to be made, the form of the organs to be constructed, and the specific instructions for their growth and function.

Now the problem Ducrocq sets himself is to ask how do the instructions thus coded in the genetic ribbon bring about an actual living creature. He postulates that this might be done by a process resembling the method by which one can automatically produce machine-tools for the construction of engineering components. The shape of any three-dimensional component as depicted on a blueprint can be defined by spatial co-ordinates, which can then be coded as instructions on to a magnetic tape, and this can be fed to a die-sinking machine controlled by an electronic device. Servo-mechanisms on the machine will then move the appropriate cutting parts according to these coded instructions.

In a similar way Ducrocq pictures the chromosomes in which the blueprint of the organism is assumed to be coded as possessing the characteristics of such a magnetic tape. The various genes contained in the chromosomes, and which in man number several thousand, are also conceived after the fashion of servo-mechanisms, each controlling part of the developmental process, and thus directing the entire construction programme of the living creature. This idea is, of course, not new in biology, but its tie-up with servo-mechanisms is new.

A word should be said about relay devices and the possibility of

their operation being coded in terms of a binary language or 1 and 0. This has given rise to a new theory, the logic of switching circuits, which is of importance in the designing of electronic computors, as by its means we are enabled to design the simplest electrical circuit to do a specific job, with a consequent saving of time and expense. An electrical relay (such as a light switch) can be in one of two positions, on or off, which may be denoted by 1 and 0 respectively, so that any system of relays connected either in parallel or series could be depicted in terms of the binary language. This would indicate which relays were being activated or not. In this way we obtain a symbolic picture of any such system of relays.

The theory of these " switching circuit systems " has been taken over and used to illustrate the functioning of the nervous system. The neurons, of which there are approximately 10,000,000,000 in our brain, can be thought of as having the character of such switching circuits, along which volleys of signals are transmitted. Each neuron may, like the man in control of a railway signal-box, allow or not allow a signal to pass, so that the complex activity of the brain, looking very much like the lights flashing on an electrical train position indicator, could be described in terms of such a binary language. It is interesting to note that Ducrocq also believes that the activity of the genetic system, which he assumes is made up of chemical relays, can be depicted in a similar way.

To return to the origin of life, that it was a unique event is suggested by the distribution of optical isomers in biological systems. The molecules of some carbon compounds can occur in two forms related to each other as an asymmetrical object is to its reflection in a mirror, like right and left hands. These forms are called optical isomers, because they deflect the plane of polarised light passed through them either to the left or to the right. Now when we make such substances artificially, our product proves to be divided about equally between the two " mirror image " forms, but as a rule in all living systems only one form appears. Though very frequently two forms are possible the specific properties of the molecules found in living systems depend on this rigid selection of one structure only. This great molecular asymmetry of biological systems is probably the result of an initial slight asymmetry in the early stages of the development of life, which has become accentuated in the later stages.

Ducrocq conceives the history of evolution as a vast statistical calculation, since he asumes that the procedure underlying evolution resembles the Monte Carlo method, which involves making repeated trials (or sampling) by random methods. In this case the data sampled is the information stored in the genes of the living creature. In sex-reproduction, for example, he supposes that the programme inherent in the chromosomes of any animal is a statistical average of the programmes of its parents from which they were derived. Nature may then be said to behave rather like a statistical laboratory; one concerned with the continued improvement of the species.

Ducrocq claims that heredity has used such a statistical method of experimentation on millions and millions of living creatures, and thus automatically improved the species. With the acquisition of a sufficiently developed nervous system, living beings acquired a brain and some measure of intelligence, though of a rather lowly kind, since it remained tied to concrete situations. By its means animals become better able to learn from experience and to cope with more than their immediate needs.

When we come to man we find that he has also the capacity for abstract thought. Human beings can use numerical concepts, and make predictions about the external world by means of symbols manipulated according to logical rules. Man's powers of abstract reasoning, by being connected with his ability to produce tools, has given rise to all the wonders of modern engineering, which finds it apogee in the electronic control devices and automation. In this way man is achieving a greater mastery over his material world, and utilising for good or evil its inexhaustible possibilities.

Ducrocq's book is to be welcomed for its courageous attempt to knit together many diverse disciplines into a coherent world outlook. Up to now cybernetic discussions have largely been restricted to the large-scale behaviour of animals, men and machines. The novelty of this fascinating study in " biocybernetics " is that it attempts to relate these new ideas to recent progress in biochemistry, and in this way to unlock the very secrets of life itself. It is to be hoped that Ducrocq's book will be read alike by the layman and the specialist, as it encourages a new and exciting approach to the phenomenon of life.

W. Mays

Translator's Note

IN this translation I have been at pains to make the language as understandable as possible to those who have no instruction in the sciences. Nothing is gained by the use of ultra-technical jargon.

In one respect, French has an advantage. The key term *asservissement* is both a very generalised and a very precise word for the logical concept of one system triggering off another which applies both in mechanics and biology. It is curious, but perhaps to be explained by the profound dichotomy of thought in these matters, that the only word we have with this meaning, derived from the very suitable Latin root *serv*,* is rather a prefix than a word in its own right—*servo*—and is in common use only in engineering.

It has in this pioneer work on biocybernetics seemed only logical to insist on the maximum use of words compounded with *servo*, and I have prefixed it in some cases even to the word *control*. This I have done because it is so essential not to think of organic " controls " solely as mere signals triggering off certain processes (such as myosine changes for muscle contraction), but to bear in mind the way in which one system, by a very slight expenditure of energy, sets in motion another system, utilising a larger expenditure of energy. Without this awareness it is impossible to understand either the grandeur of man's achievements in themselves or the way in which, as M. Ducrocq has so brilliantly outlined, they are so as the logical culmination of a single basic process.

Other points of terminology should be self-explanatory. Here and there footnotes are added, to help out with names which may be obscure to those whose scientific knowledge is

* It is interesting to compare the Slav root *rob* in robot, with its sense both of work and slavery.

relatively slight. The following additional remarks may be added: French *hasard* has as a rule been rendered by " chance ", yet here and there I have used " hazard " or " the haphazard ", mainly to emphasise that it is not a mere mathematical concept that is intended, but rather the sense of a baffling disorder. Though *être* is frequently rendered by " creature ", I have in many places preferred to speak of living " entities ". This is to generalise the reference to the maximum, since, although in the given place the author may be speaking specifically of animal forms, in fact he is concerned with the organised living unit of matter. For this reason, too, " matter " has in the main been preferred to " materials " (for instance, in speaking of what an entity is made), for here the French word *matière* automatically generalises and concentrates the mind on the organisation of matter. Similarly, though " plant " and " vegetable " are here variously used, I have often used " vegetable " where the specialist might today have used " plant ". In any case, all forms of vegetable life are not what most people would call " plants ", and not only do we still talk of the " animal, vegetable and mineral " kingdoms, but in such a book as this it is useful to have at the back of one's mind the sense of graduation from mineral to the two other divisions of " natural objects ". I have also here and there used Ducrocq's Latin term *substratum* rather than " medium " because I think it serves a useful purpose, to indicate the environment from which an entity is formed and by which it lives. There is about the word " medium " here, so it seems to me, a hint of a suggestion that the basic environment of raw material has been deliberately provided by some *deus ex machina*, whereas it is one of the main purposes of this book to do without such factors.

I most cordially thank Dr. W. Mays, of Manchester University (who contributes a preface), for the patience with which he has read my text and discussed many points. Nor in acknowledgements should I leave out my author himself, and I express my gratitude to him for the readiness with which he has agreed to more footnotes and even alterations in his text aimed at making the thesis more accessible to a wide English readership.

ALEC BROWN

Tarrant Gunville,
March 22nd, 1957.

Introduction

CYBERNETICS? Cybernetics a general explanation of life? Both its origin and its wonderful development?

Yes, that is the theme of this book.

The suggestions of classical physics certainly got us nowhere. Nobody was satisfied with the attempts the science of our schools has made to solve the mystery of the transition from the inanimate to the animate or the growth from the first minute traces of animate matter—living its autonomous life and self-reproducing—all the way to ourselves. But today, as *homo sapiens* is beginning to establish a higher level of living altogether—one based on automatised machinery which really will work for him—we have new information and new concepts of relationships which at last provide a master-key to it all.

The great error of academic science has been to persist in maintaining a dichotomy, an opposition between two worlds, the worlds of physics and of biology, which it insists on viewing as if they worked in different ways.

The world of physics is shown to be based on hazard, on random action, that is to say, on disorder. From this the physicists worked out their great principle of entropy, by which the element of disorder in any system left to itself always tends to increase.

This is regarded as " natural " for the mere " reason " that for every way of establishing order there are thousands of ways of achieving slight disorder and thousands of millions of ways of achieving great disorder.

In other words, the physicists only needed the law of probability to explain this alleged unavoidable and irreversible trend of the universe to " evolve " ever greater disorder. One needed merely to regard a city abandoned to nature. Did not weather changes,

corrosive action, possible floods and fires steadily increase the disorder? As the years went by, did not the deserted township's essential machinery rust up? Its buildings all grew dilapidated. At last they crumbled into a state close to chaos, with only very slight vestiges of any order remaining.

So much for the "inorganic" world. On the other hand, academic science points to the allegedly different "organic" world. Here it is the privilege of something called "life" to be capable of replacing natural chaos by regular structures, a process which becomes glaringly obvious with man, whose story culminates in the systematic organisation of the world. The principle of a struggle against the haphazard is inherent in all forms of life. All plants, all animals, take up raw materials from their "inorganic" environment and use them "cleverly" to make good their own wear and tear and also to make replicas of themselves—to reproduce. This all takes place by a machinery which implies order and plan. The higher forms of life, apparently, possess this creative faculty in the highest degree, using it to fashion order from disorder, both inside themselves and outside.

These ideas are a century old. The physicists sensed that such problems of order and disorder were perhaps more important even than those of energy which had formerly attracted most attention. For energy is conserved. Though it may assume the most varied forms—mechanical effort, heat, electricity, light or sound, these are all merely transformations of it. The same quantity of energy is always to be found. On the other hand, in other phenomena there were certainly real changes in the quantity of disorder, and it was this that the physicists labelled entropy.

It was then concluded to be out of the question to establish any real link between physics and biology. There could be no such synthesis because the natural law of physics was this law of the growth of entropy, whereas the basic law of biology was the decrease of entropy. The philosopher Bergson defined life as "the struggle against entropy". This biological law seemed an astonishing one, precisely because it thus seemed to run counter to what were held to be the "normal" laws of physics.

And what is our new information, which changes all this? It is the fact that we can today achieve by cybernetics machines of a totally new kind: machines which themselves are capable of creat-

ing order, that is to say, machines which are capable of acting on the outer world in the same way that life does. Like living things, these machines by themselves perform "controlled actions". We think here not only of experimental "electronic animals", the study of which is proving so fruitful, but also all sorts of regulating mechanisms, including the machine-tools of automated industry. For such machine-tools are theoretically even capable of acquiring their own raw materials, as well as fashioning them into definite products. The cardinal feature of all this automation of which all scientific thought must at last take account is this: such machinery, by reason of its servo-mechanisms, is just like life in that it tends not to increase but to decrease disorder.

The philosophical implications of this are tremendous. The notion of the struggle against the haphazard has assumed a new aspect. In place of the classical distinction between physics and biology, the cyberneticist finds himself forced to recognise that the ability of an *effector*—a term used to generalise the concept "machine"—to create order or disorder *depends in essence on its structure*. What materials are used in the *effector*, and so forth, ceases to be of first importance. The prime consideration becomes the set-up. According to how it is organised, the same material may tend to create either disorder or order. For instance, a certain substance, if used in a bomb, may well create disorder. But if used in a factory to turn shapeless raw materials into a series of shaped articles, it creates order.

Once we see that order or disorder are essentially an organisational problem, it begins to be clear why in the realm of natural action order should be the exception. Since order calls for a particular set-up of the elements, it cannot arise except as a result of previous order. On the other hand, given the initial creation of order somewhere in the system, that initial order will clearly be able to give rise to new "orderings" capable of creating increasing quantities of order. The fundamental difficulty is that initial step, the creation of the first ordering of elements which can start the whole process up. Illusory indeed when the primary system embraces a very large number of elements to expect chance to do this. The situation, however, is not quite the same if at the atomic level we consider merely a small number of elements. The likelihood of a very small number of elements getting arranged

in an orderly set-up is not at all inconsiderable. Were such an initial ordering to be achieved, there seems no reason why it should not multiply infinitely.

This is precisely the scheme which unfolds in the world of living things, for living things are natural machines capable of creating order.

Here is the theme of this book. Starting with a review of the great epic of life, we are going to see that this has consisted in the appearance first of animate things, then of a steady succession of other living things which have been improvements on those preceding them. From this general process we shall be able to unravel the underlying plan of it all, the waging of the great struggle against the haphazard and the generation of order with ever more powerful means.

Having in this way indicated the general scheme, I propose to explain how this all started from the first tentative stirrings in the fluid environment of this world in its earliest stage, with the appearance of organised aggregates of atoms which were both capable of self-reproduction and of self-improvement. This will be followed by a survey, stage by stage, of the creation of ever more evolved forms of life, till we have the appearance of the animal and vegetable species with which we are familiar today.

In this way I hope to provide some understanding of the implacable logic of this great natural process.

CHAPTER I

The Great Conquest

AS curtain-raiser, let us spirit ourselves back over the principal stages of life's great Odyssey. What an amazing story it is! The history of all life! Yesterday still barely conceived, today it is the greatest story of all time—the tale which shows why today our earth should offer us such richness of feature, such fantastic variety of things both animate and inanimate, such wealth of interaction between them all. The initial stages today look like wall-paintings ruthlessly broken up, buried under the soil, events and things no human eye ever saw, no photographic film ever recorded. Then we discover that those thousands of years which have passed all left their imprint in the soil, leaving messages thus preserved in the earth itself for man to decipher. The great miracle is indeed that modern science has known how to touch the past with its magic wand and reconstitute the history of all the rocks and layers of soil beneath us, classifying fossils and dating strata by their radio-activity count, till where once we could only speak vaguely of ages which followed one another, now we can affix a precise measure of time to our finds. Yearly now we provide ourselves with subtler techniques of research. For instance, we can already reconstruct the very climate of a long-vanished epoch by our analysis of the atoms which make up the limestone of creatures which were alive at that remote time.

Thus by the techniques he has recently invented man fashions sensitive films which he tosses back over the great millennia to examine the distant past and compile at last a history of all life. In the very near future the precision of his findings will rival that of documented history. This, if he is at the same time scientist and poet, is to unravel an adventure story, in fascination and

magnificence surpassing anything the human mind had ever imagined.

. . . . .

Let us take ourselves straight back a thousand million years. (See Fig. 1.) We find that our earth has been in existence a long time. It already possesses land masses and oceans. Just as it does now, it speeds round and round in space, on that never-changing course about the sun, which, just as today, takes it a trifle more than 365 days, while all the time, once in twenty-four hours, it revolves on its own axis, so that day, during which the sun regularly sends it warmth and light, is always followed by night.

However, we do not find everything the same. There is no blue sky, and the sun's rays never reach the earth. They are intercepted by a dense pall of cloud. This gives the milky blueness of the sky a dirty, menacing appearance.

The fact is, here, 1,000 m.* years ago the earth's atmosphere is most peculiar. Not only is it heavily charged with water vapour, by reason of the general temperature being much higher than that of today, but it also contains quantities of two gases which, to put it mildly, we should find completely unbreathable. These are ammonia, a combination of nitrogen and hydrogen gases, and methane, a combination of carbon and hydrogen (known as marsh gas).

But if the atmosphere appals us, whatever are we going to say about the soil? What we behold is more than anything else like those papiermâché " end-of-the-world " moon landscapes which we sometimes see in exhibitions. There is not a trace of vegetation to be seen anywhere, not even a blade of grass. For that matter, should we expect to find grass in a world without anything for grasses to grow in? For that lovely, soft carpet of cultivable soil upon which almost wherever we go we tread today—and never pay any attention to—simply did not exist. The very concept " agriculture " is therefore utterly nonsensical. On all sides, all that we see is granite, or basalt rock. And were we to sink shafts, to explore beneath us, we should find not a trace of coal or petroleum. Even the metalliferous ores which are mined today, and

* In this book millions are regularly indicated by m., so that 2 m. = 2,000,000.

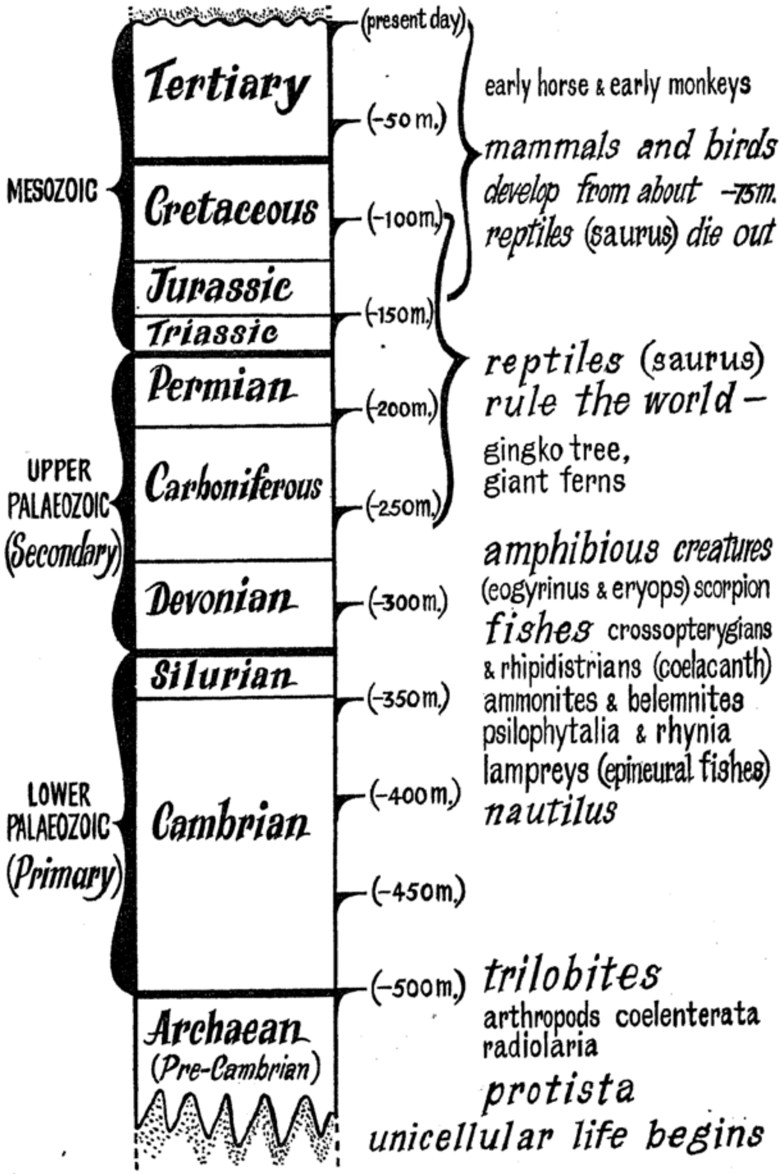

FIG. 1. GEOLOGICAL PERIODS

A table of Geological Periods (the indications in the right-hand column relate to examples mentioned in the text). *See Chapter One.*

we tend to think have always been there, are missing. *Even they were yet to be created by the great process called life.*

These barren continents which are not so much land masses as a carapaceous covering of the earth are also—this surely goes without saying—totally devoid of animal life. There is no bird's song to echo in the heavens, no insect's buzzing. Indeed, how could such creatures breathe in this atmosphere, and what would they eat? This earth of ours, 1,000 m. years ago, is merely an arid rocky globe, its sole occupants certain physical forces, which act on each other. These forces appear in the form of the winds or eddies caused by the earth's motion through space and by the temperature and pressure variations between one part of the earth's surface and another. Whenever the equilibrium of the skies is upset, there are torrential rains. The water thus precipitates streams into low-lying areas, to form lakes and seas. These waters rise and fall twice daily in tides, but their waves roar only on deserted rocky shores. Our eye would fail to find a hint of the lovely sandy beaches on which today we take our pleasure.

Such is the face of our earth 1,000 m. years back from today. It is a world from which one might well think nothing could ever be expected. The only life was that of the rocks. Indeed, we might well suspect that it was doomed for ever to be another so-called " dead star ".

Yet the contrary is the case. Everything is already fated to change. A great process has already begun. For, in these seas of the Pre-Cambrian age (as geologists call it), which we are here observing, the phenomenon known as life has already appeared. The first living creatures are already in existence. They are in the waters. At first sight, they seem very unpromising. They look like no more than mere specks.

The minute forms of life which we have in mind are those minute organisms the protista. They consist each of one single cell. They are indeed only visible with the aid of a microscope. Principal among them are little flagellate things, " whippers ", which flick their way through the water. Of these, one can hardly say whether they are animal or vegetable. Apart from them, there are also numerous bacteria, and water-borne plankton is already fairly dense.

In distinction from the microscopic creatures, however, there

are also some which are visible to the naked eye, real colonies in which numerous cells are associated. For instance, we see examples of volvox, measurable in inches, and even sponges of sorts and radiolaria.

Viewed with a terrestrial eye, it all seems to add up to very little indeed. Nevertheless, these creatures are the initial phase of a fantastic process of development, and though that development is at first hesitant, no more than the faintest of whispers, it becomes increasingly insistent, fated to manifest an irrepressible drive, till at last, of itself, it assumes a dominant role on the stage of our earth, imposing on it an ever stronger will, one, moreover, which seems to have no limits.

At the outset, however, the process of development proceeds very, very slowly, rather as if nature were planning the shape of the story of Ancient Rome, which took far more time to conquer the little province of Latium than subsequently to master the whole Mediterranean basin. We are to see hundreds of millions of years go by before the seas are populated by the coelenterata, animals which really are little more than improved sponges. With the arthropod, indeed, we do get a little farther forward, for in this we have an animal definitely endowed with precise shape and also an internal organisation. This achievement was an event of supreme importance for the future evolution of living things. But it was still not till the primary age that any really great development began.

The primary age—more usually known today as the " palaeozoic era ", whereby we emphasise that it was the era in which the first important forms of life appeared—begins appreciably towards —500 m. (as in this book we shall designate 500 million years before our era). It was to last till —190 m. These 310 m. years of the palaeozoic era we divide up into periods named after geological strata found in Britain. We distinguish the Cambrian, the Silurian, the Devonian and so forth. The Cambrian lasted from —500 m. to —400 m.* This Cambrian period is the one in which we are first offered an astonishing fairyland of ever richer forms, succeeding one another at an ever faster rate.

About —500 m., in the oceans (to which life was for a long time yet to be confined) there appeared a creature which embodied a

* Hence, of course, the " Pre-Cambrian", referred to above.

development which was sensational. This was the trilobite. Its name describes its remarkable essential feature. It was divided into three parts, or "lobes". For the first time there was a living creature fashioned in three sections—head, thorax and abdomen.

These trilobites first put in an appearance as little creatures about the size of fleas. But soon they saw their dimensions increase, till they were as large as prawns, then as large as lobsters—of which, indeed, they were the distant ancestors, though they never attained the abilities of the lobster, let alone its perfection of form. Indeed, when we come to look at our reconstituted trilobites, we cannot help being struck by their crude aspect. They are really no better than more or less shapeless masses, on which we can discern markings which indicate the three divisions of the body. At the same time, this is decked with the strangest of attachments.

Very slowly, however, certain trilobites underwent a lengthy process of further development, which extended beyond the limits of the Cambrian period. They even acquired eyes, some of them simple, others complex. But in spite of this, they remained one of life's failures. They were limited in the means at their disposal. It was as if they were initially constructed to a faulty formula, one which provided an insufficient foundation for much ultimate improvement.

From −400 m., however, other forms attract our attention. The 70 m. years of the Silurian period (up to −330 m.) constitute the second stage of the primary era. In the same way as later in human civilisations, with supremacy passing from one people to another as the centuries pass, we now find a totally different genus heading the great development of life. This was the nautilus, a mollusc, with a shell trumpet-like in shape, this being the creature's dwelling, either straight or curving back in a way which first suggests the spiral shell form.

Here let us note in passing that, although the trilobites completely vanished from the earth long ago, there are at the present moment a number of varieties of nautilus in the Pacific and Indian Oceans. Their shape does not seem to have changed much since Silurian days, when they were the kings of this earth, busy ensuring a future life at least by bequeathing this or that feature to many

another species. For instance, much later, we find the secondary age marked by the birth of new molluscs, belemnites and ammonites. And eventually this world of creatures which we call "hyponeural" (because their nervous system is built into their carapaceous covering, which is thus a sort of false skeleton) gives birth to an astonishing variety of other species.

Let us now, however, turn our attention in another direction altogether. For the principal fact in the history of life here, in this Silurian period, happens to be not the persistence of molluscs but the appearance of actors on the ocean stage who are totally new and very surprising. They are—the first fishes. Here life plumped for a totally different formula—the *epineural*, that is, with the nervous system inside. We see their first representatives towards —390 m. They were at that time still extremely rudimentary. For instance, they had no jaws, for which reason we dub them agnathous. The lampreys of today are the degenerated descendants of these agnathous fishes. Their only means of imbibing food was to suck it in through a sort of rounded funnel. They had no jaws to open and close. In place of mouth they had a simple circular opening, with a movable piston in their larynx to serve as tongue.

The agnathous fishes were also finless. This means that the first fishes must have moved about like giant flagellates. Little by little, however, the agnathous fishes developed coats of mail, formed of bony plates. Towards —360 m. their numbers began to dwindle, to give place to the so-called placodermatous fishes, fishes, that is to say, with a hard outer shell, newcomers which also had the first fins, and rudimentary jaws!

We now come to a new period, the Devonian (—330 m. to —270 m.), our third canvas of the primary era. This proves to be *par excellence* the age of fishes. What we now behold is the disappearance of the placoderms, coupled with the entry on the scene of the true fishes—cartilaginous and bony. Now the great realm of the vertebrates had come into being, and the living world developed in a new direction.

Certain among the bony fishes were to prove of particular importance. I think here of the so-called crossopterygian fishes. The striking characteristic of these is the structure of the fins. They cease to be directly attached to the fish's body, but begin

to be articulated on special bases, borne on a scaly support standing out from the animal's body.

The crossopterygians' fins, indeed, had turned into veritable paws, webbed paws. And now these fishes were fated to undergo a strange experience. They give birth to two lines of descendants, two lines which in due course knew fates as different the one from the other as could be imagined. One branch was marked by a policy of astounding conservatism: it included the notorious coelacanth, a creature which recently proved to have lingered on to this day in the waters off the Comoro Islands in the Indian Ocean. The other branch, typified by the rhipidistrians, gave rise to an astonishing line which finished up by the surprising feat of quitting the watery habitat altogether, to bound about on dry land! For the rhipidistrian fishes happened to find themselves equipped with internal nostrils, and this put them on to the systematic elaboration of lungs, which in turn enabled them to shift from a life in the water to a life on dry land, breathing air.

Now it so happens that just as the curtain fell on this clearly marked-off period, so decisive for the direction in which life was to develop, our earth was the scene of a tremendous geological development which was to effect a profound transformation of its appearance. The event is completely understandable. We merely need to pay attention for a moment to a very, very slow but continuous process which was going on all this time in the earth's crust. To a considerable depth this was steadily contracting. This shrinkage inevitably caused crumpling, and that crumpling did not take place evenly, but in spasms. There had already been one important crumpling movement toward −600 m. We know it by the name of the Charnian Fold. However, this was of little concern to life, which then existed only in that very early aquatic form. Conditions, however, were quite different when towards −150 m. the Appalachian Fold took place, causing a great transformation of the surface of the continents, with the catastrophic appearance of a mountain chain stretching round the Northern hemisphere from present-day Scotland to Northern Siberia.

It was while the world lived through that astonishing geographical reshuffle that living creatures first emerged from the water, in the form of the first amphibians, the labyrinthodonts, the earliest specimen of which appears to have been the eogyrinus.

This creature lived in swampy areas subject to periodical drying out. Its trump card was its ability to continue to get about when there was no water left. Like the eel, it could make its way across dry land in search of another swamp. Another labyrinthodont was none other than the notorious Texan eryops, rather like a crocodile with stumpy head.

If now we glance at the dry-land masses, we find our scenery very different indeed. Whereas at —400 m. what " land " there was lent the earth rather a sinister aspect, being all arid and devoid of vegetation, in the Silurian period the world saw the first attempts at plants. These were the psilophytalia, direct descendants of marine algae (seaweeds), still to be found in marshy places. They were as yet only a few inches high, but they were definitely dry-land plants, for they were equipped with somata, which made respiration feasible, and they also had cells capable of transmitting sap. One of the most primitive of these plants, the rhynia, was still without leaves. Its spore-case developed at the termination of its branches, and its roots were mere prolongations of the main stem. Nevertheless, it was a fascinating parallel to the contemporaneous trilobites. For here too was a tripartite layout, in the sporecase, the stem and the subterranean prolongation of the stem, all of which was in effect the first adumbration of the leaf-stem-root system of plants.

Later, when in the Devonian period the waters gave life to an explosive development of fishes, on dry land too came a development which was parallel, nothing less than the appearance of the first trees, the first mosses and the first seed-bearing heathers.

In the following period, the Carboniferous, which tangibly lasted from —280 m. to —220 m., after this installation stage, vegetable life developed intensively. Those 50 m. years were characterised by the growth of dense forests. Now moss-trees, multiple rushes and conifers, and heathers as tall as trees, thrust heavenwards. But, mark well, so far there was not yet one single flower!

Now, however, followed the great innovation of this period—interrelations between the animal world and the vegetable. What happened was that the former set to work to live on the other. Here were laid the foundations of a policy which was to bring in great dividends. What is most remarkable, too, is that this sudden

attack of the animal world on the vegetable took place on two fronts, which, as far as one can see, were quite distinct one from the other. What had happened was that the world of living creatures—animals—had split into two groups, one of which (the more recent, that of the backboned animals) was setting to work to conquer the dry land of the world.

The vertebrates in their invasion of the dry land had in fact been preceded by another invasion, begun long before. Representatives of another division altogether of the animal kingdom had established themselves on dry land well before —300 m. These were those fascinating creatures, the scorpions, which as far as one can see were absolutely the very first inhabitants of the dry land. One still recalls the excitement caused when Milne-Edwards told the French Academy of Sciences that the Swedish scientist Lindstrom had found a Silurian fossil of a scorpion on the Isle of Gothland, for that was certainly at a time when nobody thought the animal kingdom had set foot on dry land.

The scorpion is certainly a very peculiar creature. It is an extremely elementary form of life, a try-out antedating the final structural formula which, pursued in another direction altogether, produced insects. Insects did not put in their first hesitant appearance till after the onset of the Carboniferous age, doing so in very differing forms. The principal were the eugereon, very slightly like the bed-bug, contemporaneous with a giant dragonfly and the meganeura, with a wing spread of as much as two feet. These forms, however, were not to survive. True insects did not appear till flowering plants appeared. With these they were to follow a strikingly parallel line of evolution. Sucking insects developed together with the cryptogamic plants, while pollen-eating insects appeared together with phanerogamic species.

The principal line of advance was now unquestionably that of the vertebrates. We have already remarked on the first invasion of the land masses by amphibians. This was merely a prelude. From —250 m., however—that is, at the height of the Carboniferous age—we find reptiles. At first they were most cautious in their appearance on the scene. But it is as well not to be deceived. Their initial shyness was merely in the first act. Afterwards followed a fantastic expansion of terrestrial vertebrates in many directions. Indeed, starting from the Permian period, in which

the realm of the invertebrates was completed by the appearance of winged insects—beetles and grasshoppers—and the world was subjected to a great glaciation which drove life into the equatorial zone, an early reptilian branch produced creatures which already were impressive, specimens reaching ten feet in length. Some, like the pareiasaurus, had short, massive limbs, others, like the dimetrodon, had thinner legs and were able to move fairly fast. But the most interesting thing we should note here is that now—in the cynodonts (reptiles whose denture is very like that of the dog)—certain reptiles were clearly evolving in the direction of mammals. This development, however, still required a lengthy period of time for its completion. These trends seem to have plunged into the darkness of a tunnel. They were not to emerge again for another 100 m. years. But emerge they did!

For the time being, it was reptiles pure and simple which ruled the dry land. In these millions of years they assumed the most fantastic of shapes, unbelievably varied. To such a point did they proliferate, and for so long, that science speaks of the " Reptilian era ". Another name for it is the Mesozoic. It lasted from —190 m. to —70 m. As a rule we divide it into three periods, the Triassic (—190 m. to —150 m.), the Jurassic (from —150 m. to —110 m.) and the Cretaceous (from —110 m. to —70 m.).

In this era there were reptiles which returned to a marine life. Such were the ichthyosaurians, whose shape suggests that of fishes (they sometimes reached over thirty feet in length), while their jaws were equipped with numerous pointed teeth (in some cases up to two hundred).

Other reptiles took to the air. These were the pterosaurians. The most celebrated of these was the pterodactyl. Their bones were hollow, as were those of birds some day to be. Also, bird-like, they already had elongated necks. The general structure of their bodies was indubitably reptilian.

The great majority of the reptiles, however, remained terrestrial. These are collectively known as the dinosaurians. At the beginning of the secondary era, their size was reasonable (only a few yards). But very soon they assumed terrifying dimensions. The diplodocus, gigantosaurus, brontosaurus and atlantosaurus reached sixty, eighty, even one hundred feet in length. They were herbivorous creatures, in all probability both inoffensive and stupid.

They were not capable of moving their imposing bodies at any speed. Most of their time was thoroughly taken up by the task of masticating the many hundredweights of herbage and scrub which were essential to the daily nutrition of any one of them.

There were, however, other reptiles which were carnivorous and terrifying. Among these were the ceratosaurus, and, still more striking, the notorious tyrannosaurus, a most menacing monster, whose yard-long jaws were equipped with innumerable dagger-like teeth four to six inches in length. Towards −100 m. this individual became the great killer of the world of living things.

Meanwhile, vegetation had undergone a striking evolution. In the Triassic period true heathers, the cycadalia and the gingkos appeared, and throughout the Jurassic period this latter family underwent a great expansion. As everybody knows, the gingko is a tree whose lovely leaves, arranged in a fan shape, fall in the autumn in a golden snow. It is still to be found in Japan (where it is grown in temple enclosures) and its peculiarity is that it does not propagate itself by fruit but by rudimentary seeds called ovules which it drops straight into the soil. The secondary era also saw a tremendous development of coniferous trees—pines, sequoias, cedars, cypresses, palms. The latter were to be found much farther north and south than today because the general temperature of the earth was still higher than it is now.

Our globe was still to undergo further convulsions, and towards −150 m. the so-called Appalachian Fold took place. There are traces of this in France, in the "Hercynian V", formed by the mountains of Brittany, the Central Massif and the Vosges. These today are old mountains. Erosion has worn much of them away. Originally, they must have risen to about 16,000 feet above sea level.

Now new actors appear on the scene, in the form of mammals. They emerge from that long tunnel of darkness to which we have referred as apparently swallowing up a special branch of the reptiles. The first mammals appeared towards −150 m., to commence a totally new genus of terrestrial animals. By reason of having warm blood and a highly developed nervous system, they were basically much better designed than the reptiles. The mammalian age proper was, however, still far off. It was really only the first primitive mammalian essays which appeared in −150 m.,

strange half-way house creatures, laying eggs but suckling their young when they hatched out. We know them as the monotremes.

About 10 m. years later, birds appeared. The first real one was the archeopteryx, which, as well as feathers, still had teeth and a long reptilian tail.

Now the story of the mammals became a repetition of that of the reptiles. For quite a long time the newcomers were very retiring. Their main preoccupation seems to have been to produce better models of themselves. Towards −130 m., we find the first marsupials, creatures of which the kangaroo is a vestige. At this stage of development the embryo underwent two stages of growth. It grew for a time in the mother's womb, but completed the process in an external " marsupial " pouch.

At last—towards −80 m.—mammals with the placental system appeared. The advantage of this was that it enabled the embryo to complete its development in the uterus. It was while all these changes were being accomplished that the birds appeared—those with both reptilian tail and teeth at the beginning of the Cretaceous age, towards −110 m., those without this tail, but still having teeth, in −90 m. And that concluded the secondary era.

There now followed an interlude between the secondary and the tertiary eras. This, the Cenozoic period, brought a tremendous scene-change. For the first time, the vegetable kingdom assumed the outward appearance which we today know. In the secondary era it was dominated by conifers. But the Cretaceous age saw the wholesale appearance of flowering plants, with the parallel development of butterflies and bees to gather their nectar, while climatic changes brought about the first appearance of the trees with which we are familiar: oaks, beeches, poplars, chestnuts, willows and suchlike.

The most extraordinary change, however, in the 10 m. years between −70 m. and −60 m. (in the first part of the Eocene period, −70 m. to −45 m., which constitutes the first part of the tertiary era) is the almost complete disappearance of the reptiles. It was only a few species which remained, in the main harmless, or at least not playing any great part in life as a whole, creatures apart, like the crocodiles still to be seen in the rivers of Africa. Simultaneously, the mammals underwent a sensational expansion, with a real explosion of new types, whereby in a relatively brief

space of time the ancestors of most of our present species were produced. What is most remarkable is that this explosive development seems simultaneously to have affected the Old World and the two Americas.

Now the mammals in their turn grew bigger. For at first they were really astonishingly small. The early horse of the Eocene, for instance, was about as big as a hound of today and the early elephant was as big as a pig. They were due to develop, passing through evolutionary stages which in many cases we have been able to reconstitute with great fidelity. Thus, in —55 m. the ancestor of the horse race—also that of the ruminants (of which the camels and llamas are the most primitive representatives) —is the diminutive hyracotherium. This creature, widely distributed in America, had a jaw more like that of a man, and a paw which ended in five fingers. Towards —50 m. it gave rise to the eohippus, which was larger, with more evolved " paws ". There were now four fingers on the front legs, three on the rear. Later in —45 m., we find the orohippus, which was still larger. Towards —40 m. appeared the mesohippus (with only three fingers to each hoof), in —25 m. the parahippus, and towards —20 m. the merychippus, still larger, its legs terminating in hooves which had only one finger. After that came the " true " horse, that which we know today.

The elephant's past history is much the same. Starting with the moeritherium (towards —50 m.), a creature with no means of defence, and a jaw rather like that of the modern horse, in —40 m. it had evolved into the palaemoston, with its upper jaw curved down, much like an eagle's beak. Towards —20 m. had appeared the mastodon, and in this the upper jaw had definitely evolved into an embryo trunk. In later generations, this went on growing longer, till it reached its present form.

Here, in passing, we may observe that just as certain reptiles once resumed an aquatic life, so now did some of the mammals. Thus arose the cetaceans (whales and so forth).

Side by side with these simple cases of development, we also find ramifications of fantastic diversity. The complexity is exemplified by the carnivorous mammals. Towards —40 m. these split into two great stems, the pinnipeds (principal successors of which are the seals and walruses) and the fissipeds, which in

turn produced a great number of variations, some becoming completely carnivorous, to end as cats, tigers, lions, hyenas and civets, the others to evolve alimentary systems of all intermediate kinds, including the omnivorous. In this group the principal creatures to emerge were the ursidae (bears) and the canidae (dogs), the differentiation of this latter sub-group continuing to our day in the countless forms of dogs.

This is the general scheme of developments. Nevertheless, even though from the beginning of the tertiary era most types were represented, one must at the same time point out some very important exceptions. Certain species were to take much longer to put in a first appearance, but were to write the most extraordinary chapters of our history.

It was towards —60 m. that the "pseudo-apes", the lemurs, appeared. Like the true apes, of which they were a sort of first sketch, they had paws which ended in true hands, which enabled them to hang on to things in a special way. On the other hand, the lemurs still had an elongated muzzle and, yet more striking, a poorly developed brain. Today they hardly exist outside Madagascar (the makis or indris), but at the close of the Eocene their importance was considerable. Climbing into the tree-tops, they spread over the whole earth, where for a period they were the noblest form of life, producing certain species (the tarsiers) the flattened face and globular skull of which adumbrated the ape.

The ape proper appeared towards —45 m., at a time when the earth underwent one of its periods of geological transformation. This was when the great folds which produced the Himalayas, the Rocky Mountains and the Andes took place. For a long time sea tides rose high in the Alps.

Just like all other mammals at the start, the first apes were very small. They are known as the parapithecans. They were not much above six inches high and seem to have been concentrated on the shores of the Mediterranean. Towards —35 m., however, they disappeared almost completely, making room for much larger apes (from two to three feet in height). These were the propliopithecans.

Between —45 m. and —30 m. we recognise the change from the Eocene to the Oligocene periods, and the period from —30 m. to —10 m. we know as the Miocene. It was now that took place

the main development of these apes which set out to conquer the world. With them, we draw close to the final result of all this development, till in the Pliocene (—10 m. to —1 m.) we finally see (particularly in Africa), ape-men known in standard classification as australopithecus. These ape-men walked upright and knew how to make use of stones and sticks. They lived a tribal existence and may have survived till fairly recent times. At this point, however, our attention is drawn elsewhere, to a newcomer, one who is very interesting indeed.

This newcomer was the hominoid ape, appearing on this earth by reason of the very same mechanism which we have been observing in other species. The new actor creeps most surreptitiously on to the badly lighted stage, and contrives to remain unobserved till a considerable time after his entry. But when the eye does catch him, it is with utter amazement.

Hitherto we have been counting gaps, and periods of time in tens of millions of years. Here, however, we have reached our last million. There seems relatively little room left—compared with the preceding ages. Yet it was to be most prolific in events. It is an age enclosed in the framework of the glacial ages in which the earth knew great cold, and glaciers spread from the North Pole to cover half of Europe and North America too with ice.

What caused that chilling of the air? It certainly puzzled geologists for a very long time. Yet when we take all the facts into consideration, it may have been completely natural. The climates of our earth are conditioned by the inclination of its axis to its orbit, the precession of that orbit, the variations which take place in the eccentricity of the orbit and the precession of the axis of rotation. Each of these factors varies very slowly indeed. But from time to time it is feasible for their various effects to coincide in such a way as to give the earth an extremely cold climate. The reconstitution of the earth's past climate made by Milanković on the basis of calculations of such coincidences furnished findings which certainly fitted the facts of geology to a remarkable degree.

Each of those glacial periods completely changed the conditions of life and altered the face of the earth. There was a remarkable succession of four such glacial periods. First, towards the year 600,000 B.C., came the first, the so-called "Günz Glaciation".

This was marked by violent shifts of the earth's crust in the Far East, particularly in Indonesia, with the folding and piling up of the mountains of Sumatra. Now, curiously enough, very soon after this (namely towards 550,000 B.C.), pithecanthropus and sinanthropus first appeared in this region. These two species may have been identical. Numerous skeletal remains of them have been found at Trinil, on Java, and in China.

Sinanthropus and pithecanthropus were of the stature of very small men. They may have had an extremely rudimentary language. They did not know how to make tools, but they did use objects they picked up as tools. They were omnivorous; no doubt, on occasion, cannibal.

Then follows another chapter. After an inter-glacial period (corresponding in time to Chellean and Abbevillean) came "Mindel's Glaciation". This was towards 430,000 B.C. The long inter-glacial period which followed, which is characterised by the red earths of the Alps and Italy, saw the appearance of so-called Heidelberg man. This new ancestor of ourselves was apparently able to make himself tools. He probably had a more developed form of language.

Then comes the third chapter. About 180,000 B.C. occurred the "Riss Glaciation", and the inter-glacial period which followed saw the appearance on earth of Solo and above all of Neanderthal man, so called because just over a century ago (in 1856) the first specimen of this species was found in the Neanderthal Valley, near Düsseldorf. Neanderthal man can hardly be qualified as primitive. As a matter of fact, his brain capacity was larger than our own, and the study of the skeletons we have recovered (there are about fifty of them) reveal clear indications of specialised activity. Neanderthal man manufactured many implements. He buried his dead. Nevertheless, he still looked very wild. His brow was receding, his frame in some respects archaic. Just like australopithecus, he may have lingered on till fairly recent times.

Finally, our fourth chapter: about 100,000 B.C. the latest glaciation began. It went through various phases. The final onset of great cold began only 20,000 years ago. It drew to its conclusion about 10,000 years ago. The general thaw-out of the masses of accumulated ice which followed resulted in a general rise of the water-table. In this way, in the course of some 40,000 years the

seas may have risen more than 400 feet. This caused tremendous changes in the shape of the land masses. One important transformation was the pouring of water into the north-westerly hollow of the Eurasian land mass to form the North Sea. Britain and the continent of Europe were formerly joined by lowlands where there is now sea. As a result of this great movement, enormous areas of the land surface were flooded, and many islands disappeared altogether. The disturbances continued up to the age of history proper.

After the last great glaciation, another forward stride of evolution. *Homo sapiens* appeared. It is not out of the question that our genus first put in an appearance earlier, in the days of Neanderthal man. But if he did, he did not make his mark. He springs eventually from a distant differentiation. After the fourth glaciation, we find him plentifully, in the forms of Cro-Magnon man,* Chancelade man and Grimaldi man. These three types may all have been ancestors of present-day men. And when the last glaciation was all over, towards 10,000 B.C., after the preparatory Magdalenian period, there was a wholesale invasion of the world by our precursors. These now spread to nearly every part of the earth's surface, even traversing Asia to thrust into North America across Behring Strait. Thereby they retraced the steps of the horse, which, originating in America, moved west to reach the Old World.

Thus the history of life reached its culmination point, in man, the demiurge capable of knowledge, purpose, thought, the user of tools and master of purposive action on his environment, the living creature which, so doing, very soon succeeded in turning the living world upside down, destroying forests to grow his crops, causing tangible increase in the sedimentation caused by erosion and both intentionally and unintentionally destroying many animal species, while on the other hand he brought about the multiplication and eventually even the transformation of others.

After a certain period of gestation, early man gave birth to civilisation. Thus arose the Babylonians, with their pride and their material wealth. There also appeared the extraordinary technological ability of the human mind. The wheel was invented, and then, some time after, the dynamo, to give rise to industry which

* The name is that of a grotto near Eyzies in the Dordogne hill country in France, a veritable prehistoric metropolis.

in our time has totally changed the earth. Man has now reshaped much of his habitat to suit himself, constructing cities, roads, dams, factories, canals, exploiting the minerals under the surface and turning the world into a tightly knit network of his many activities, till at last, recently, he has even set himself the aim of conquering other planets and imposing his will on them too.

. . . . .

Such is this astonishing adventure story of life, which, starting from quantities of apparently inert slime in the warm seas of Pre-Cambrian days, became a tremendous development the thunder of which today deafens the world, and would seem to be powerful enough to subdue the whole universe.

But then we begin to ask questions. We cannot confine ourselves to marvelling. We become anxious. To what end was all this? What is this force which we call *life*? What is it after? Why did it appear on earth at all? By what amazing and subtle interplay of forces did conglomerations of atoms become living aggregates, in course of time to assume the form of a cedar tree, a beetle or a shark?

Yes, this story of the development of life which we have just run through is really most disconcerting. There seems to be some system about it all. Above all what strikes us is the realisation that living creatures seem to have developed in a series of waves, each successive one more effective than the preceding, each genus in turn apparently obeying some specific evolutionary law, till the whole sequence of genera shows a rising succession of steps in anatomy, physiology and mentality. For instance, Nature produced the head towards —700 m., with the first anthropods, the lung in the dipneust fishes at —300 m., and warm blood when it reached the level of the marsupials at —125 m. A French thinker, André Cailleux, has made a fascinating table of development. He took the notion of a scale of mentality which J. Romanes first suggested, at the close of the nineteenth century, in his *Animal Intelligence*. Perfecting this, he drew up a classification of great interest. Using a series of tests based first on directed reactions, then on problems of learning, selection, association and so forth, he correlated the intelligence of animals with their anatomical perfection and their order of appearance on this earth.

The result is remarkable. It shows a definite correlation between anatomical effectiveness and mental improvement. Moreover, this table seems to tell us even more; the various stages seem to have followed one another by a logarithmic scale of time. By this we mean that the levels reached by animals over equal spaces of time followed the order of a number series in which each successive number is double that which precedes it, i.e.: 1, 2, 4, 8, 16, 32. Thus, we find only instinctive behaviour up to the appearance of vertebrates about —300 m. At this point the first hints of intelligence and learning appear, to develop with constantly increasing rapidity up to *homo sapiens*, with his powers of imagination and logic.

This observation, however, does not answer our question. It only serves to make the story of life still more intriguing. For it does not tell us the basic reason for this logarithmic process of development. What mechanism was it that in this magic way produced these successively "improved" species? We find transformations which are quite astounding. The abundance of the forms which life assumes today is really amazing. What is the key to all these mysterious changes, to achieve which each genus, each species, seems to spur the next one on still faster, as if all were engaged in a stubborn relay race?

In the course of the ages, certain families have vanished altogether. But others, on the contrary, defying the millions of years between with a persistence which is truly amazing, have persisted. It would seem that the record here belongs to the world of bacteria. One of these is outstanding. This is the leptothrix, which does seem to have existed for 1,000 m. years without interruption or change. This curious creature draws its energy from nothing less than the combustion of iron (iron "burns" by rusting). We have mentioned, too, the nautilus and the scorpion. The case of the coelacanth is no less sensational. This strange, primitive fish had been thought to be long since extinct. Then, in 1938, a fisher netted a live specimen, and deliberate search for the coelacanth has since then obtained for us a dozen specimens.

When we take into account all the variations, we can tot up a total of millions of species of life, animal or vegetable, adapted to the most diverse conditions. There is life on the earth's surface, life in the air, life in the oceans. There is life too deep down

in the waters, seaweeds in different-coloured stages at various depths, capturing various bands of solar radiation. There is life in the polar cold just as there is in tropical forests. There is even life in the sulphur springs of Barèges, which come out of the ground at a temperature of 149° F.

Further, life offers us all possible sizes, from the viruses or micro-constituents of plankton to giant trees with trunks 100 feet in circumference and summits which tower more than 300 feet in the air. There are creatures offering us every possible colour, every possible form, every feasible mode of existence, every caprice of geometry. The panorama which offers itself today to our sight in this great book of life is indeed astounding. Is there any key to the combined development of improved forms and multiplication of extraordinary diversity? If so, what is that key? That is what I intend to try to answer.

CHAPTER II

Biological Automation

IT is the diversity of life that disconcerts. It has assumed such an extraordinary variety of aspects during the hundreds of millions of years of geological time. There is also such astounding variety—no less than before, indeed—in the forms which life assumes today. We need only take what strikes our eye as we wander through the woods in spring and observe Nature playing her lavish tricks in that gentle fairyland of green. Indeed—let us note this at once—the diversity is all too enchanting. It prompts us to dwell only on life's myriad varieties, that is, on the countless haphazard forms which it has assumed. We are so bemused by the variety that we tend to forget about the system which must be implicit in it all. Yet that system is what it really does pay to elucidate.

Let us use an analogy to make quite clear what we mean here by the " system " implicit in living creatures. Let us imagine a sort of historical radio exhibition, not one of new sets only, but a retrospective one. There are stands with every possible type of receiver, from Branly's coherer, the receiver using galenium, all the way up the ladder of crystal receivers and thermionic-valve receivers, receivers with head-phones and receivers with loud-speakers, receivers powered by batteries or accumulators and mains receivers, sets with frame aerials built in and sets which need outside aerials. We should find among them plain ebonite boxes with a multiplicity of knobs controlling rheostats and rows of switches. Out of these might stick impressive glass bulbs. There would also be upstanding marvels of fine joinery, divided into compartments, and dainty little suitcase or handbag plastic things. Here too we should see a miniature receiver contained in a lipstick container and there a mammoth walnut cabinet embracing under

one roof radio and television receivers and gramophone, all complete with a multiplicity of valves. Now let us imagine one of Fenimore Cooper's Red Indians who has never heard tell either of electric waves or radio reception brought to the show and later required to give an account of what he saw. Is it not clear that all he could tell his hearers would be the outward features of the various sets? He would talk about the number of knobs, the colour of the cases, the shape of the dials and so forth.

This is not to say that his story would not fascinate another Huron. It might even enable that other person to identify some of the sets. But particularly if the publicity men who arranged the exhibition had done so from the spectacular standpoint, ignoring any sense of the science of it, it would tell him absolutely nothing about the essential principles of radio. Well, that is exactly the position of our friend strolling in the woods, discovering life as he or she goes and content merely to revel in the ravishing spectacle offered.

We can go even further. Imagine our Huron gets the idea into his head that he would like to make an analysis of what these radio sets contain. So with the aim of furnishing his fellow countryman with a detailed description of their insides, he takes them to pieces. What would his account be now? He would talk about quantities of copper wiring. Some of it, he would say, is bare, some of it is varnished, some of it is wrapped in rubber, silk or plastic (i.e., insulated). He might then set to work to analyse the materials involved, even achieving a true statement of the chemical composition or the colour of the insulation and varnish. Similarly, he would describe the condensers and resistances as "little tubes filled with some complex stuff". He might suggest that they were put together in rather a peculiar way. And were he to dismantle some of the thermionic valves, to find out how they were constituted, he would say that all they had inside them was a number of little scraps of metal, which were not even all of the same shape. He might be puzzled to discover that the scraps of metal varied in form, number and position from one valve to another.

I doubt whether, in the light of this comparison, the reader can help thinking of those long descriptions of living creatures to be found in biology manuals. In them you find an enormous

taxonomical * accumulation of detail, with all the observations ever made of the organs, the vessels, the fluids discovered in living creatures, none of it, however, rising above the level of the descriptive naturalist.

Not that it is in the least our intention to underestimate, let alone denigrate, the labour accomplished in past centuries in either biology or medicine. All this has been a tremendous labour, which has furnished a classification which we could not well have done without. What is, however, bad, and rather silly, is that far too often has it been forgotten that all that labour was merely the first step. Just as the radio mechanic knows very well that all the sets in the world are merely variations on one fundamental scheme, made possible by certain accessories and adapted to various demands, we should look on the world of living things at last not so much as mere biologists but also to some extent as engineers. For what is the essential question at the bottom of it all? It is—once we can forget the dazzling fantasy with which the living creature confronts us—to find out if under all these individual set-ups we cannot find some general guiding principle. After that, comes the next problem: why nature worked it all out, and how the implementation of the principle could gradually be improved, producing more and more striking variations from the original.

That is the approach to the world of living things which I propose to adopt in this book. What I want to ask of the reader is that he too should try to look on forms of life not as he actually sees them with his eyes, but judged from the standpoint of a certain functional system, a system such that all these taxonomic details which are usually recorded in " natural history "—height, appearance, sensory system, the way of life, the food of the creature—cease to be things in their own right and become merely the consequences of the system. This indeed is why I prefer to make no detailed mention of the famous theories formerly proposed either to explain the functions of living creatures or to make sense of the grand phenomenon of the evolution of species. As we know, three names have dominated these theories of evolution. Lamarck suggested progressive transformation of the animal by its environment. Darwin based his views on the idea

* Taxonomy—the " science " of named classification.

of natural selection, that is to say, on the survival of the fittest, the creatures best fitted to win the battle of life. Finally, de Vries laid emphasis on the possible effect of mutations which brought about sudden modification of characters from one generation to another, after which, without any apparent logical reason, the change became hereditary.

Certainly, once the biocybernetic view of the matter is outlined, it may be of interest to try to see how the classical theories might fit into it. But for the moment, however, let it be understood that we are going to observe the world of living things as far as possible independently of all the usual interpretations. I wish to suggest we examine the world of living things from the standpoint of pure logic. To this end our first task is to assemble information on the observable characteristics of that world.

THE LIVING THING AS SERVO-MECHANISM

Let us then consider any living thing, simple or complex, vegetable or animal, and for a moment look at it with the mind of an engineer. We are bound to be struck by a fact which is common to all things. This is that it is able to make use of relays. Here the term relay is used in the sense given it in cybernetics. This implies a disequilibrium between the energy used to perform an act and the energy which at a given moment causes that act to be performed, the process involved being intrinsically one of ordering or commanding an action.

The idea is familiar to any who have studied cybernetics. However, for the reader with no special knowledge—and in any case to make the general notion crystal clear—let us pause for a moment to consider this idea of relays. It is fundamental, not only in engineering, but also in biology, and logic. One of the great merits of the industrial cybernetics of our age is that it furnishes us with apparatuses which (quite apart from the immediate interest we may have in using them as automatic, robot devices of the most varied kinds) provide us with the opportunity of studying the logic of relays in very simple mechanical applications of the idea.

It is easy to grasp the notion merely by considering the servo-brakes fitted to many cars. (See Fig. 2.) An ordinary brake, of

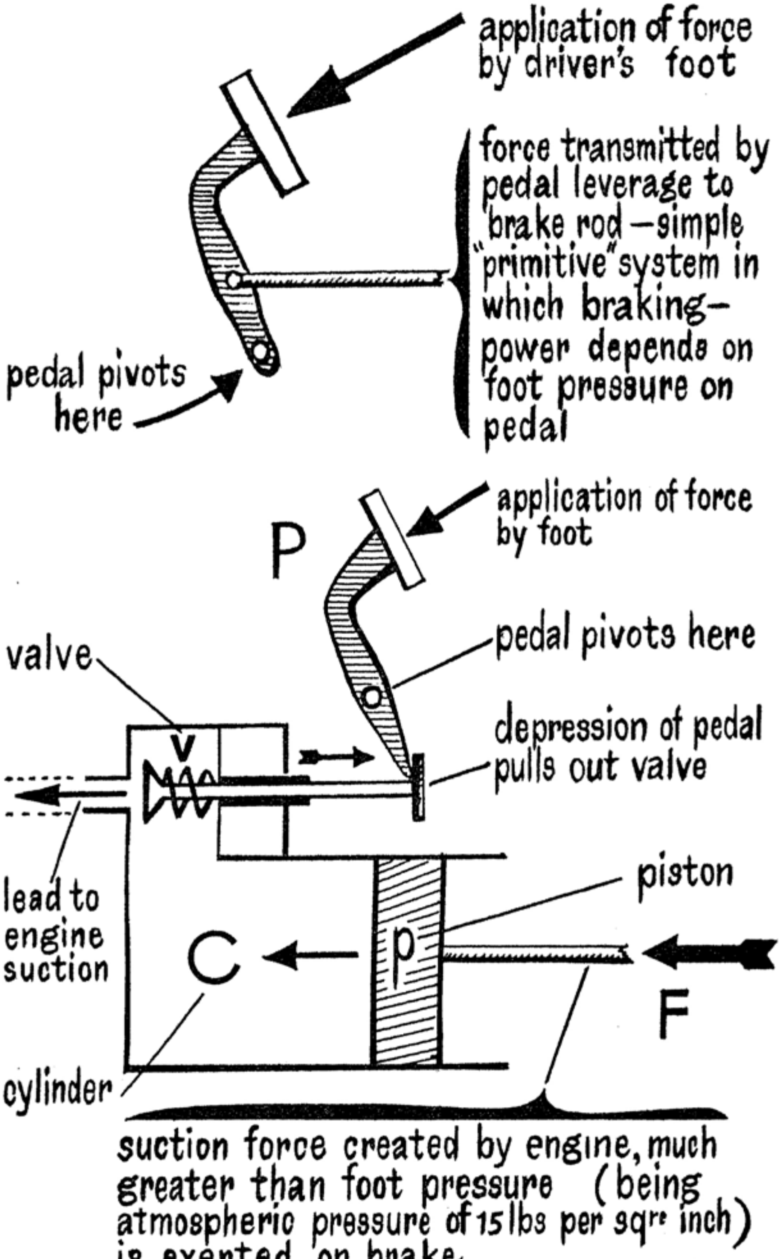

FIG. 2. THE SERVO PRINCIPLE
Simple foot brake and Servo foot brake.

course, consists of a pedal which either by cables or rods or by hydraulic piping moves cams so as to press " shoes " against " drums " which are integral with the wheels. In such a system the force required for braking is applied directly by pressure of the foot on the pedal. This clearly means that the braking power depends on the power of the leg muscles employed.

The servo-brake is rather different. It is designed to exert the necessary force on the wheels—which in the case of a large car moving at high speed may be considerable—without any need to apply anything like that force to the pedal. It is designed to make use of an independent source of energy and bring this to bear on the brake-shoes. The role of the foot pedal is then reduced to that of controlling the unit which supplies the independent force. It merely has to put the brake-shoe into direct linkage with the independent source of energy, a vacuum chamber, evacuated either by the engine of the car or by a special motor—so that this does the actual braking *for* the foot. With this set-up, a minimal effort with the foot on the pedal can be made to bring as much energy as we desire and plan to bear on the actual brake. The same sort of thing can be found in the steering of some modern cars.

A similar principle is embodied in the servo-controls of heavy radar aerials. These can only be moved by electric motors, which swing them into the desired position. The only difference is that here the whole business is much more complicated, because not only does the engineer have to make sure that the aerial is moved to face in the right direction, but also that the speed with which this is done is under perfect control, so that movement ceases at the exact moment when the desired orientation of the aerial has been attained.

There is, however, one fundamental idea which is common to all these examples. It is the notion of a source of energy which can be drawn on at will, the role of the person controlling being reduced to the function of actuating the control. In short, we have in each case a genuine relay of energy. The idea of any such relay, servo-mechanism or " control " is essentially that of two systems which are linked, that, for instance of the brake pedal, and that of the actual brake-shoes. In simple systems, the work done depends directly on the force applied, and the laws of classical mechanics

rule. With relay control, we have a disproportion between two different systems. *The second system is, however, so set up that it is obliged to respond to the movement in the first system, but without this having to provide the much more considerable energy necessary for the work such response involves.*

It is not difficult to see the profound significance of this disproportion. The simple notion of an increase of energy does not explain it. The idea is absurd. Nor does conservation of energy enter into it. In our example have we not emphasised that the relay is feasible precisely because there is another source of energy available? The energy that came from the starting-point of the process is not important, but its application is. What does this mean but that the factor which is increased is not that of energy *but that of organisation*. It is a certain set-up which results in the utilisation of a secondary source of energy being dependent on a primary source of energy. It is the servo-mechanism which ensures that the orders of the first stage are effected by the second.

Here we have the essence of it all: servo-mechanisms amplify orders. Servo-mechanisms are typical of those artificial devices which, as we suggested in our introductory remarks, are able to diminish entropy. Here is a key notion which we need to keep constantly in mind. Leaving rather obscure for the moment the problem of the actual amounts of energy involved at one point or another—one in which yesterday people were too exclusively interested—let us express the situation in terms of entropy. Let us keep clear before our eyes the way in which one system controls the other if it gives it more order than it loses itself.

Now let us spend a few moments in the world of industry. We may observe that the principle concerning order lies at the bottom of many contemporary applications of the idea. The moment that the primary system does not have to do the actual " work ", we may use the most trifling of signals for it. This means that our relays may be set in motion by a mere ray of light or the infinitesimal electric current of a radio detector.

This means that by these devices a machine can be made to depend on a series of signals. This is precisely the idea that modern industry more and more seeks to utilise. For example, a machine-tool today is capable by itself of cutting out any profile, when controlled by the insertion of a template—a pattern cut out

of metal plate. A feeler follows the edge of this pattern. As it moves this way or that, its movements control those of the tool. This is the crudest possible application. With a little more style one can make a machine-tool into which one needs to feed, not an actual pattern, but merely a drawing of the desired product. In this case it is a photo-cell which picks up the tracing of the profile and relays it to the tool. Or one can go a step farther. The profile can be translated into a code. The code indication of angles, curves, lengths, etcetera, is recorded on a steel ribbon, where it appears as a series of magnetisations. This record is then fed into the machine, which is equipped with the necessary apparatus for interpreting such instructions and controlling the necessary tools in accordance with them.

At the moment of writing, it is in fact this latter method which stands highest in favour. The reason is that this is a very elastic device. It is capable of conveying a wider range of instructions. Therefore it is more practical. The reader will no doubt be aware that till quite recently these magnetised ribbon records were being used principally to record music. In them, the vibrations of the sounds of music are transformed by translating the sounds into electric impulses which change points of the steel ribbon by successive magnetisations, of intensity varying with the music. When played back, the magnetisations pass in front of a device which interprets them back into electric current of proportionate type, which is then amplified and passed to a selector. Similar variations of magnetisation can be made so that when translated back, a machine is ordered to perform various movements. One only needs a ribbon long enough to contain a programme of operations detailed enough for the machine-tool to perform all the operations required to transform its raw material into units of the prescribed shape and size.

Further, which is most important, this control principle offers us the possibility of the special situation provided by the introduction in the supply of instructions of a closed circuit, with what one calls " feed-back ". The moment the energy of the servo-control system is very much weaker than the energy doing the work it may be made to draw on this, in such a way that the relay ceases to act, a closed circuit being formed which automatically stops the whole system. A simple example of such a closed-circuit

control is provided by an automatic central-heating system. Basically, the output of a central-heating unit is regulated by a control knob, moved by a human operator. This action in itself is of course a servo-system, since in it the enormous heating energy is controlled by the very slight amount of energy required for a man's fingers to turn the knob. When we so build our central-heating system that the effect of turning the heat regulator is secured, not by anybody actually turning a knob, but by a little device actuated by a thermostat (which is merely an appliance which measures the temperature in the building which is being warmed by the system), we have established such a circuit and feed-back. If the temperature in the house is too low, the thermostat moves a lever, and this * increases the power output of the central-heating unit, or, vice versa, if the temperature of the house rises above a certain point the control decreases the output. That is to say, using such a unit, one decides in advance on one's " normal " house temperature, say 62° F.,† and there is nothing more to worry about. The feed-back controls the central-heating unit for one, so that this maintains an output of heat sufficient to keep the air temperature in the building at 62° F.—assuming here, of course, that the unit can cope with the work, for no feed-back control will ever make a boiler do more than a certain amount of work.

Now let us turn back to the living creature. We find in it all the features of these systems of control and feed-back. For example, in the superior forms of life, how obvious is the existence of a reservoir of energy, which can be applied at the appropriate moment to any one of a variety of actions. Though we are not incessantly eating, we do build up a reserve of energy in our systems which we can use whenever we want for various muscular actions. Our control knobs are our motor-nerves. These too act through servo-mechanisms, for the energy realised by the muscle results from the combustion of glucose already contained in it, whereas the nerve which gives the order makes use only of a very small potential of energy indeed, moreover, one derived from another source altogether, in the praxic area of the brain, from

* By opening flues or fuel-supply valves, turning on electric booster motors or oil-burner fans.

† A usual English standard; in America the standard is higher.

which the nerve takes sufficient merely to provide the servo-signals which control that combustion of glucose. Generally speaking, any form of muscular action is in response to some sort of such control. Very broadly speaking, the muscles of man or animals, at whatever stage of evolution they are (for the fibrous tissue of the protista can be looked upon as playing a muscular part), are motors which do not work at just any time or in just any way. They work by reason of orders created in the living creature, in consequence of messages, external or internal.

The disproportion between the nerve energy and the muscular is sometimes most striking. Take the case of the animal which sights an enemy and takes to flight at top speed. Work out the ratio between the energy which the creature immediately begins to use and that which originated its movement of flight. That initial use of energy involved no more than the reception by the retina of the eye of a certain number of photons of light, communicating the picture of the feared enemy, and photons of light are very weak forces indeed.

Here we may observe that in the higher creatures such expenditure of energy is mainly controlled by a hormone, adrenalin, which the suprarenal gland secretes. It is typically illustrative of the servo-mechanistic system that the relative importance of this gland, hence its size, is directly proportionate to the rapidity with which the creature is likely to want to call on its maximum energy output. Thus we find the suprarenal glands of tigers and lions are much larger than those of their human counterparts.

We also find servo-mechanisms controlling very different functions. A good example is the way our stomachs secrete gastric juices, merely on the basis of visual information about appetising food.* Next, we must notice that, besides these simple examples, we also find in living creatures the execution of controlled programmes the scheme for which was already implanted in the creature when it was born. Such controls produce astonishingly complicated actions which we sometimes ascribe to a special force called " instinct ". Their complexity can indeed be amazing. For instance, we see birds able to fly soon after hatching out, and very soon after this making their own nests, even tying fibres

* Indeed, a mere printed description of a dish may " make our mouths water ".

in knots to do so, which means that the beak has to perform a series of very exact movements, all rigorously prescribed, performing an elaborate programme just like the machine-tools we considered earlier. In other cases we find such programmes of action are drawn up by the living creature itself, after it has first gone through a sort of learner stage. An example of this is man's own ability to walk.

Besides, should we not really look upon it as laid down in a programme contained in the living entity itself that this, once born, should develop through stages which are the same for all representatives of the same species? Within certain limits of variation, height and weight increase in the same way in all specimens, till they reach the adult size. Indeed, we do know that this programme of bodily growth is directly dependent on a substance known as thyroxine, which is secreted by the thyroid gland.

Most striking still, in living things we also find the feed-back system of control. It works in man, for instance, when he picks anything up, or in an animal when this captures its prey. The arm or claw muscles are so many servo-controlled devices, which work under the instructions of the brain, by reason of signals collected by the eye. For it is the eye that enables the man to estimate the distance between his hand and the object he wishes to pick up, or the cat to judge the distance between claw and prey. Thanks to the complexity and delicate precision of the eye and the great richness of analysis which the brain accomplishes, and thanks finally to the great wealth of possible movements of his joints and musculature, man is able to develop a most complex set-up of feed-back controls and thereby to change his environment.

Our organism also embraces a fantastic number of inner servo-mechanisms, working in circuits to maintain proper regulation of the workings of our internal organs. For instance, the amount of glucose in the blood is kept at a constant level. This is thanks to an automatic servo-regulation system worked by the liver. This organ is able either to stockpile glucose in the form of glycogen, or to reduce the stocks of that chemical by the commands made by insulin, which the pancreas secretes. Similarly, blood-pressure is maintained at a constant level. This is thanks principally to the aortic and sinocarotid pressure receptors. When the pressure goes up, these bring about a slowing down of the heart and simultaneous

vasodilation of the tissues, which also automatically helps towards the desired result—a lowering of blood-pressure. Likewise, the respiratory centre of the rachidian bulb is excited by carbon dioxide (" spent air "). This enables it to control our respiratory rate, so as to maintain the pressure of carbon dioxide in the blood at a constant level. We also have the regulation of the amount of calcium by the parathyroid glands.

Further, there is that remarkable automatic regulating system which maintains our body temperature at a constant. It is an extremely complex set-up. Independently of the hormones, a special set of cells near the hypophysis works as heat regulator. It first gets its information as to our body temperature from the blood-stream, some of which is by-passed through it. It gets additional information by reason of being the terminus of nerves which bring in waves of information about hotness or coldness from the special sense organs all over the body dealing with those sensations. If our temperature tends to drop, the regulatory centre at once directs a speed-up of the expenditure of energy by the organism. This is essentially achieved first by the muscles, then by the liver. Even without contracting, the muscles are able to increase their expenditure of glucose. All this is balanced by a different mechanism protecting us against heat loss by the process of vasoconstriction (closing up of the skin pores).

THE TWO FACES OF CYBERNETICS

It would therefore seem that living creatures are capable of controls just like the machinery which the modern engineer constructs with servo-mechanisms built into it. The only *a priori* difference is that one set of controls is artificial, the other natural.

Is this intended to imply that the same means are made use of in the two cases? Not in the least. We can at once indicate profound differences, both in materials and scale of operations.

To the engineer, machinery suggests metals. In all our artificial servo-systems the classical basic material is steel. The typical situation is that of an impressive block of iron, the " bench ", fitted with tools which bite into other blocks of iron moved up into position by a conveyor belt. Admittedly, industry today makes more and more use of plastics, because it is so easy to shape such

materials. But the mould which shapes them and all the machinery which is essential to that work nevertheless remains a matter of metal. In every case industry is obliged at a given point in its processes to melt the matter which it utilises, which very often obliges it to work at very considerable temperatures.

Biological processes make use of utterly different materials. Moreover, they all proceed "in the cold". We shall see that they rely essentially on organic substances, which is the same as saying: stuff which is easily moulded, adaptable, associative. It consists of plastic substances of extreme perfection, capable of being built up from small components, capable of being fitted together, broken down again, then reassembled according to some new formula. Here, too, every part consists of an incredibly large number of minute machines which, as we shall see, work in parallel, so that breakdowns or momentary deficiencies do not matter. This, however, also makes the working of the whole assemblage sometimes fantastically intricate. Let us put it that in one single human organism there are more separate pieces of machinery than in all the factories of the world put together!

In short, the machines which compose a living organism are both unbelievably numerous and extremely small. Here is the second capital difference between the world of living things and industry. The biological factory is conceived on a totally different scale. Its component parts are atomic. This is a point which we should never lose sight of, though it is too often overlooked. The layman is only too ready to get it into his head that today the engineer is capable of making a true replica of the machinery of life. In fact all he is able to reproduce artificially are certain of the servo-mechanisms of the living creature. The delicate intricacy of the biological machine sometimes reveals itself in astonishing fashion.

Take, for instance, the butterfly. Here we have a piece of machinery the lightness of which is astounding. In this insect body there are no engines, unless those muscles which move the wings, or the sense system or the digestive organs, deserve that name. If he examines the insect closely, the engineer finds spatial relationships which have nothing in common with his machinery. Compared with the butterfly's muscles, our lightest electric motors are enormous masses. Besides, to make the comparison fairer,

we should not forget that the mere equipment we need to keep sensitive control of any of our engines is itself bulky. For besides the actual engine we must have its controls, and these must consist of electronic units fitted with thyratrons or amplifying circuits.

No doubt about it, this absolute difference of scale between our electro-technical industries and biology's industries is of capital importance. Perhaps it is clear now why we remarked above that the equations governing our servo-mechanisms are not transferable. At the same time, it enables us to make an immediate riposte to the over-confident objection which the German mathematician Bückner raised against the reduction of biology to complexes of servo-mechanisms. Bückner showed that ordinary servo-mechanisms may be represented as Pfaff-systems.* Hence once man is able to evolve concepts which go beyond Pfaff's equations, it is—Bückner suggested—difficult to see how these equations can embrace the universe of biology.

After much consideration of this reasoning, I have come to the conclusion that it ceases to be applicable on the level of atomic events. For those Pfaff equations which Bückner adduced are equations which deal with macroscopic quantities. They unquestionably fit the industrial use of servo-mechanisms. But they cease to work once we drop to the minute realm of the living cell. The moment one enters that realm *where quantum mathematics rules*, Bückner's hypotheses therefore lose their validity. Hence it is quite reasonable to think in terms of servo-mechanisms which are no longer subject to Pfaff equations, a point we feel worth emphasising.

We are thus in mechanics obliged to deal with servo-systems in which the materials used, the scales involved and hence the governing equations are very different from those of the servo-systems which interest the biologist. None the less, it is important to bring out the fact that the servo-systems in one and the other world serve the same purposes. Outside all the differences of materials, scales and equations, *the logical structure is the same*. For here, too, in living matter, we find the fundamental

* Pfaff, 1765–1825, a German mathematician best known for his work on equations. Equations, the mathematician's expressions of relationships between natural phenomena, or natural processes, are the instruments with which man contrives succinctly to manipulate and " discuss " on paper material developments in the world in which we live.

order-increasing mechanism relying on the utilisation of stores of energy under the servo-control of other, much more insignificant sources of energy, either of the same nature or totally different. This is just what we find in all our industrial servo-systems. It is the same general formula that we find abundant evidence of in the living creature.

The comparison made here is intrinsically most important. It clearly reveals the two faces of cybernetics. Cybernetics in general being the " science of controlled acts " (that is too say, of actions subject to signals or programmes), we need to understand that there are two ways of realising such controls. The relay may be purely physical, or it may be chemical. It is controls of the first sort which today industry makes use of under the term servo-mechanisms. Those of the second sort constitute the realm of biology, in which, as we shall see, farther on in this work, it is essentially chemical actions which effect the control or servo-mechanism.

FROM MACHINE TO FACTORY

Here the reader can be heard to interrupt with a question. He will admit that this proliferation of " controls " in the living organism and our formal analogy between these and industrial servo-mechanisms is all most interesting. But, he will ask, what does the comparison prove? What right, indeed, have we to pass from making an analogy to real comparison. Do I mean to point the conclusion that the living entity is an assemblage of machines engaged in a struggle with chance?

Let me try to make the point of view of this chapter quite clear. Since for the time being we lack really exhaustive information on the nature of life, what I am trying to do is to adumbrate a workable model of what life is—leaving it to later amplifications of my thesis to show whether there is any verification for it.

So let us now, within the framework of this hypothesis, take another step. Let us raise the problem to a higher level. Let us try to make a synthesis of all the servo-systems we perceive in the living creature. One thing is quite clear. They are all part of some sort of " plan ", one which covers all the tremendously complex organisation of the creature. Similarly, of course, when we enter a factory at work, we see that every single machine-tool has its

specific function in a general programme of operations, the factory as a whole being a larger organism whose various machines are so many factors exerting controls which all together combine to make the factory produce a definite material or object.

If in this way one considers machine-tool servo-mechanisms not one by one, in isolation, but all assuming their proper places in the organisation which they serve, we get our comparison between biology and industry on to a higher level. The automatisation of the whole work of a factory is the technical step which today goes by the name " automation ". What we need to consider now is whether life itself is not perhaps to be visualised as a vast biological automation. This is the suggestion we are now going to examine. But first let us try to get beyond today's actual industrial applications of the idea, and understand the deeper sense of automation.

THE FACES OF AUTOMATION

Now, what exactly is an automated factory? The standard notion seems to be a factory in which one has replaced machines which used to be looked after by workers with " robots " (the substitution having become possible as soon as men found out how to make a mechanical device perform the operations the human workers used to perform and to repeat them indefinitely), while in addition it has proved feasible automatically to co-ordinate the work of a number of these robots. The expansion of automation in this sense in every country in the world is familiar to everybody. It is bound to effect a profound transformation of our society, both economically and socially. But this is not our problem. Let us rather look a little more closely at *the scheme* which governs our automated factory.

In such a factory, our first impression is of a number of units, each of which is installed to effect a precise control. For instance, we need to introduce to the factory, from its source of production, a given raw material. If it is a liquid or a solid material which can be washed in, we do this by a pipe or channel, or, in the case of most solids, we use a conveyor-belt, a belt with scoops, or an Archimedian screw. But we need to let in just the right amount of the raw material and at just the right speed. This we achieve by a

variety of devices, automatic balances of one sort or another, which in fact work by collecting data regarding the intake of the material and according to that information control the speed of the various sources of motive power which effect the transport. In given cases, we can arrange further for automatic machine-cutters to cut the raw material into pieces of given shape, and we know that this work will be effected automatically with great accuracy. No matter whether we adopt the solution of the transfer machine, or have a chain of workshops looked after by one unit, the control-actions of which have been calculated with nicety, since here we require the machine to produce a completed article. It may be a case here of assembling manufactured parts and even of ensuring a number of finishing operations, such as stoving or painting.

All this organisation has one single purpose, that of bringing together the multifarious controlled operations performed at the various stages in the work to combine in the manufacture of the definite finished article. Each partial process, when completed, is a factor in the over-all system of the final assembly of the product.

There are, however, various possible stages of automation, and there is much heated discussion about them. Born in the second world war, automation at first assumed a very rigid shape. To manufacture definite finished articles, engineers thought they needed to construct ultra-specialised machines, each made specifically for the mechanical production of an object with well-defined characteristics, and incapable of adaptation. This was indeed the simplest solution, when it was a case of almost unlimited mass-production of an article.

However, instances arose in which this way of tackling the matter was bound to prove catastrophic, for between the moment of inventing the machines and that at which these at last went into production, engineering techniques everywhere had evolved further, so that before it even started producing the machine was unusable, being incapable of adaptation to the changed demands.

It was then a great step forward when Leaver and Brown's methods were adopted. These two engineers hit on an interesting idea. They made a classification of their various machines based on the operations they performed, and gave these operations numbers to indicate them. The first task in the production of a given article then became that of indicating the operations required

for its realisation. What was striking in this method was that the exact details of the operations in each case—the movements of the tools, the shape of the units—now became indeterminate. They were only to be communicated to the machines at the last moment, by giving them their programmes of work—in the form of a perforated card. By modifying the perforations, the same machine could be made to modify the shape of the thing it produced. In recent years at international exhibitions of machine-tools we have seen this principle of giving directions by perforated cards in general application.

However, even this solution is today being left behind in favour of the use of a strip of steel recording ribbon. (See Plate I, facing page 96.) I have already described the principle by which magnetisation points on the ribbon record are by means of amplifiers capable of controlling all the movements made by the parts of a machine.

Perforated cards and magnetic ribbons alike have meant a great advance over the former rigid systems of specific built-in cams which were merely capable of endless repetition of one precise movement. By the new methods, the machine-tools are adaptable in response to the ribbon applied to them. One could put it like this: there is now a specific tune for every operation.

With a factory consisting of machines set up in this fashion, if the decision is taken to change certain features of whatever is manufactured it is only necessary to insert new ribbons. This in fact is what is now done in a really modern factory making motor-car engines, when the decision is taken to change the cylinder bore or slightly modify the cylinder head.

However, at its present stage of development, automation does still require human initiative, if not in the actual processes at least in their preparation. A change in the bore of the cylinder involves more than mere different treatment of the cylinder-block. The pistons too have to be changed. This means altering the con-rods, the gudgeon-pins, the little and big end bearings, and so on and so forth. Hence, when the decision is taken to " change the model ", this means a completely fresh re-calculation of all specifications. A new plan of operations for every machine-tool involved must be drawn up. This work of course involves much desk-work by the " back-room boys ".

It is nevertheless an error to think that we cannot get over that

difficulty. Automation, I must insist, could include this preparatory work too. There is nothing against the calculation of all the new dimensions caused by a given initial modification (by increasing the cylinder bore) being carried through by an electronic brain, which would of itself magnetise the necessary instructions for the machine-tools on a series of new ribbons. To the electronic brain would be fed the bare instructions: "*Increase the cubic content of the cylinder from 600 ccs. to 630 ccs.*" With this directive alone the brain would proceed to perform all the other calculations, so that without any delay the factory would be producing identical engines except that—they had larger cylinders, and every other necessary modification had been made in proportion to this. We have written *would*. The word, of course, *should* be "*will*".

Ah, the reader may interrupt, that is still not total automation, for we still need the human factor, if only to put forward the demand for a larger cylinder! However, that operation too could be automatised.

Here the incredulous reader will argue that, even if a factory is as "evolutionary" as this, that is because it is ultimately directed by intelligent beings, and that explains everything. At the head of the factory is a manager, who chooses his engineers, and these are kept in touch with the progress made by all other industries. If this factory makes motor-cars, the engineers, apart from other work, also gather information about shortcomings of their products on the road. When they take account of all these indications, they are able to draw the necessary conclusions about improving existing models and producing better cars.

True, the engineers do all this. But must one conclude that these engineers are really engaged in a free exercise of their faculties, or that their work inevitably involves thought? Not in the least. If their role is analysed, we see that neither the manager nor his corps of engineers possess that initiative which is ascribed to them. There is no *liber arbiter* in their work. They do not do "whatever comes into their heads". Their work is strictly limited. It is confined to working out *the solution of a problem which they themselves have not posed*. This might be formulated as: "Taking account of subsequent events in the outer world, what are the wisest modifications which could be made in our existing model?"

Now, since the problem is not posed by the manager or his engineers, it is possible, I must insist, for both the collection of the requisite information and also the solution of the problem to be devised mechanically. We can suppose the factory to be equipped with an enormous indexing system which automatically records all that has happened to all the cars put on the road during the preceding year and at the same time gathers all possible information on new technical achievements concerning the raw materials and finished parts of motor-cars in general. It must be admitted, electronic computers could utilise all this information and work out the specifications of the new model to be produced in the light of new experience. What must we conclude? Simply this: that the moment such equipment is installed, we have not merely automation in the more restricted sense but automation plus progressive improvement of the cars made by our factory. The only proviso (an essential one) is that our various machine-tools are elastic enough in their operations to be adaptable to all the modifications which may be required of them.

In other words, the notion that improving a model necessarily demands the intervention of human thought is an error too readily made today. This error repeats that of the monkish copyists 500 years ago, after Gutenberg's invention of a printing machine with movable type. For this is how those copyists argued: " Writing is the expression of thought, therefore if a machine is going to write artificially instead of a human being [which was of course what Gutenberg's press did] that machine must be able to think." Not at all! The execution of a given programme in no wise implies the action of thought. Once one can formulate its programme, any operation can be automatised, and we must not forget that *working to improve an existing programme is itself a programme.*

This is tantamount to saying—and here is the kernel of our idea—if, in the world of industry, automation develops on the lines of the indefinitely continued manufacture of an article, there is nothing to prevent the designing of an *evolutionary* automative system. By this we shall in due course see our " automatic " factories regularly improving the articles they manufacture, and doing this too automatically, by taking account of the teachings of experience. This is the prospect we should bear in mind if we wish to get a fair view of all the possibilities inherent in automation.

ANIMATE FACTORIES MAKE ANIMATE FACTORIES

Now let us go back to the living creature. Is it an automatised factory? Yes, it is. All its servo-mechanisms combine for the same purpose—the manufacture of the article made by the factory, which is—another such factory, a replica of itself. Here what I wish to indicate is the property living things possess of being able to " control " matter exterior to themselves, making from it replicas of themselves. This they do thanks to a series of remarkably orchestrated operations, which include a very large number of separate servo-mechanisms, effecting reactions which take place regarding and against everything. At least, that is what the living creature would like them to do. And they operate thanks to the protection afforded by auxiliary servo-systems intended to exclude any disturbing influence of the exterior world, that is to say, to overcome the role of chance.

Here indeed we have the most remarkable feature of life, one which is common to all forms: the living machine has the property of being able to make another like itself. Of no importance, for the moment, how it does this. The bare fact is that the chimpanzee is a creature which is able to take certain other matter from the world about it and so transform it that in the end another chimpanzee is born. Likewise, working on exactly the same lines, the beetle makes another beetle and the cactus another cactus.

This is undoubtedly a form of servo-mechanism. For this assimilation process, this faculty, dominating the world of living things, possessed by a certain substance, of being able to make a facsimile of itself out of other substances, is typically characteristic of that disproportion which arises when a primary system imposes its will on a secondary system without this process being reversible. Generalising, we can speak of servo-mechanism in a living creature the moment that, starting with matter exterior to it (by a process of construction and assembly governed by a rigid complex of laws), the living unit can manufacture all the substances of which it is made to such end that these result in the production of an identical living unit. Such is the bare scheme. Obviously, the more " improved " a living entity is, the more complex an organisation will it require. But one thing is quite clear: the engineer will see in the living creature a genuine factory, organised for the

construction of an identical factory, the raw materials, to be taken from the creature's environment.

Quite clearly, this process of manufacture is completely unconscious. The animal or the plant does not know what it is doing, still less is it at all conscious of the machinery by which the manufacture takes place. Put otherwise, what we are saying is that the manufacture is " automatic ". We may assume that, once set going, the living factory works on without any direct outside intervention.

True, one may object that there is a difference between this process and a real factory and its product. If, for instance, our factory makes motor-cars, the servo-mechanism system consists of a collection of machine-tools, but the product is a motor-car. In the living creature, however, the product is a collection of machines which are identical to those which made them. But take note: theoretically there is nothing against an engineer's designing an automatic factory which assembled not automobile parts, but— the parts of the machine-tools of a factory like itself; in other words, in the last resort making a facsimile factory. Elsewhere I have pointed out that von Neumann, working on this subject, indicated the design of a number of such " self-reproducing machines ", that is to say, machines which, having the necessary raw materials to hand, utilised these to construct other machines identical to themselves. This, after all, is just what the living creature does. It is merely a factory which is able to produce a replica of itself.

In passing, we may note that this parallel has an important corollary: whereas biology and industry were once disciplines which took no notice whatsoever of each other, today the time has come for them to offer each other invaluable co-operation.

Making a study of the automatisation arrangements in a number of enterprises, I myself was recently struck by noticing that when these were functioning properly they frequently presented schemes which resembled those of living organisms. Nor should we forget that, vice versa, where yesterday the biologist saw only organs and hormones, whose functions and effects escaped him, a glance at the cybernetic arrangements which engineers have invented for industry now offer him invaluable hints about the part which his organs and hormones actually play.

Without pushing the matter farther, let us content ourselves

with saying that the comparison between biology and automation seems most fruitful for the science of tomorrow. It is capable of giving rise to fascinating parallels, be it merely when we plan the co-ordination of machines in an automatic factory. The solution, as I have pointed out, consists originally in having each servo-mechanism worked by a robot, ensuring the transfer of materials from one machine to another by an automatic conveyor. But is this sufficient? Not in the least. It is unthinkable that all our machines are going to work at the same tempo. Breakdowns are always possible somewhere in any factory. We have already noted the need to cater for some co-ordination between the various machines. The usual way of ensuring that is to furnish a central unit electrically linked with the various sections of the works, so that this can gather information as to their progress and in return instruct them on any necessary modification of their working.

But what, apart from anything else, do we find in the organism of a highly developed living thing? We find, of course, a multiplicity of various functions, the self-regulation of each of which is assured by means of glands, which exercise their controls by means of juices (" secretions ") known as hormones. But what is most remarkable is that not one of these various glands is an autonomous unit. Together, they all form an integrated, co-ordinated system. Indeed, we know what links them. They are all under the common control of the hypophysic gland, which plays the part of a central directing unit, acting on all the other glands in the right degrees by means of various stimulants.

Further, we may note that an animal's blood is the vehicle of a number of fluids which convey orders to various organs. But in industry, would it be feasible for one central brain to instruct numerous machines if it was linked to them in this way by only a single line? Of course it would. A single line would be sufficient for the transmission of a series of coded messages. These could be various sets of impulses, each set of impulses capable of acting on a particular selector, bringing it into predetermined positions by the appropriate code numbers. Have we not the spectacular example of the automatic telephone? It is the series of coded impulses which this sends out that enables the caller to get into touch with any other line on the same exchange. The blood-vessels work on this model. Though the various substances are

all mixed together in the blood, each has its specific action alone on this or that precise organ.

Finally, the factory is again like the living being in that absolute automation is impossible. Even when a completely automatised factory has been built and painstakingly organised to work to a given programme, its autonomy can still not be quite total. Chance will still play a certain role in its functioning. Any piece of its machinery may stall. The brushes of electric motors get dirty, circuits burn out, and so forth. Admittedly, one can draw up in advance a list of possible breakdowns or accidents and make provision for their automatic repair. But clearly there must be some limit to such a list, and if a breakdown which is not foreseen does occur, our factory, if devoid of any outside interference, will break down completely and be beyond repair.

But that is just what happens with living things! These are able to repair a certain number of breakdowns automatically. But the number of possible repairs is always limited. There are also many accidents which can arise and leave them impotent, because such contingencies are not provided for—accidents such as the disappearance of oxygen from the atmosphere, the intake of a poison, or, say, the breaking of a tooth in a rabbit. In such instances the living machinery too breaks down completely in the end. The breakdown takes the form of the death of the individual concerned.

EVOLUTION

If the living being is a factory able to make, not a given " market product ", like our factories, but a facsimile living being, it is surely clear that this second individual will in turn also be able to do the same, so that the process could go on indefinitely, providing us with an endless succession of generations.

Though this identical reproduction is certainly what we see in living creatures over any short period, we know very well that things are not like this on the scale of geological time. In our first chapter we reviewed the great highroad of evolution, and saw this leading to the most intricate of transformations and variations. In the scale of geological time, instead of endless reproduction of facsimile factories, we have a tendency for our factories to produce new factories which are all slightly improved models.

But this, after all, is perfectly in line with the total automation which we proposed above for industry. Here I suggest that there is nothing in the industrial field against the future seeing factories which both manufacture an article and gather information on the fate of their product and also of similar products of other factories, by which they are able to modify their product so that it should " hold the market " or " survive ". All that is required is for the factories to be equipped with information centres transmitting their data to electronic computers which would control the printing of the factory's new work programmes on magnetic ribbon controlling the machine-tools.

This is indeed to a T the process which we find in life. As I shall show, the machine-tools which make the individual are substances called enzymes, while the magnetic ribbons embodying the blue-prints are the chromosomes. I shall explain where these information centres and these computers which hand on the history of the species are situated. Thus generalised, the history of life will then be seen to be an astounding biological automation.

After all, if one considers that all the products of industry, yesterday obtained by classical methods, could be produced in factories set up on such lines of generalised automatisation, I think the astonishing parallel between the evolution of industrial products and the history of life must be obvious. Besides, one only needs to think of the changing appearance of any object, say the telephone of 1922, 1936 and 1957. In so humble a parallel as that, can we not see the trend in course of time towards the refinement and improvement of living species too?

Further, let us take a look at the transformations in motor-cars. From one year to another, the various manufacturers modify details. Here they change an accessory, there they lower the body, elsewhere they choose a slightly more powerful engine. This is all a miniature evolution which is typical. Will any of these changes last for ever? Oh no. All at once, in a year or two, a still newer model will appear, made on a substantially different formula, itself to be the starting-point of new minor improvements.

Besides, just observe to what an extent the working of a factory is a function of external conditions. Here, for instance, we see a manufacturer launch a cheap model when a slump sets in. He adopts the principle of all-steel bodies, stamped out mechanically.

Next, he utilises cellulose paints. . . . After various developments, you have a completely new popular baby car. However, some years go by before the maker shows it at the annual motor show. Even then, you may have to wait more years before it goes into mass production.

Here again one is astounded by the fascinating correspondence with biological phenomena. In the world of living things too the tendency for there to be lengthy periods of preparation and progressive improvement of existing creatures, followed by the more or less sudden appearance of new creatures, forces itself on our attention.

The great problem of the story of life is, however, that of its very " beginning ". How are we to find out why and how living creatures, however primitive they were, appeared on earth at all, endowed from the start both with this property of self-reproduction by servo-mechanistic actions on the environment and with an organisation which foreshadows the living factory, with its " programme " of reproduction elastic enough to learn from experience?

This is the biocybernetic theory which I now propose to unfold, one which aims at nothing less than showing the origin of the phenomenon by reason of which this natural process of self-reproduction appeared, starting from a collection of servo-mechanisms which arose in the principal constituents available on our earth in its primitive stage, and were destined to give rise to all this fantastic process of life. I shall endeavour to show how the process came about, and to formulate the laws by which, within the framework of this automatic self-improving process, life came to assume the many forms which we find in it today.

We are therefore now going to turn our attention to the set-up on our earth at the outset of its history and consider how, given the chemical nature of that world, it was these servo-processes inevitably developed, to evolve along the road leading to ever richer and more competent forms of life.

CHAPTER III

The Curtain Rises

IT all begins with a long, obscure period, which lasted from the final solidification of the earth's crust and the appearance on this planet of the first living creatures. We have positive evidence that living creatures already existed a billion* years ago, for we have fossils the age of which can be scientifically determined as something between —1,200 m. and —1,400 m.

The search for fossils of this earliest of all periods is, however, most unrewarding. Those we need were buried very deep indeed and have mostly been completely changed—cooked, in fact, by the tremendous pressure of the strata which have accumulated above them during geological time.† Hence it is really rather a vain dream to think that we may ever recover fossilised remains of the earliest life of all. Nevertheless, we are not far wrong if we fix the absolute beginning—at least, that of the first forms of cellular life—at about —1,500 m.

For orientation here, may I recall that we know that the total age of the earth, determined with reasonable accuracy by atomic methods, is of the order of 3,000 m. years. We also know that though our globe started out like a ball of fire freshly emerged from a furnace, the initial cooling, to provide a surface on which life might develop, was very rapid. Leaving out the various fluctuations in the process, a firm crust was formed, with a thickness amounting to some tens of miles. This crust rapidly enclosed and cut off the fire still raging inside. The result was that the initial heat was there preserved. It has remained almost unchanged

* Billion, used here in its American sense, = 1,000 m. (the European or metric system *milliard*).—*Translator.*

† Geological time: i.e., the time during which various layers of the earth's crust have accumulated on the initial outer shell.

to this day. Our earth is like a spherical thermos flask. The crust, however, being able to radiate its energy into space, at once underwent a very rapid cooling. With it, the surrounding atmosphere also cooled. This brought some of the water-vapour which initially saturated the atmosphere down in the form of torrential rains. That process gave rise to lakes and oceans. Meanwhile, the cooling processes continued, the temperature of the atmosphere and the waters gradually tending towards a certain equilibrium between the heat radiated by the earth and that absorbed by it from the sun.

The earth cannot have been far from attainment of this state of equilibrium about —2,500 m. Hence we have to envisage quite a lengthy period, at least 1,000 m. years, during which the earth enjoyed physical conditions which we may qualify as " normal ". During this time, as we shall now see, matter must have undergone a stupendous process of organisation for various forms of living matter to have appeared on the scene.

We need to maintain constant awareness of these circumstances. For were we—as people do but too often—arbitrarily to fix the time when there were the first visible signs of life as the moment when life began, that would be to condemn ourselves never to understand the process of the origin of life at all. For, were we to make this mistake, we should be failing to take account of the process before life had already succeeded in its first stage of expansion.

For the really fundamental problem of life is not to be seen in why, once cell life existed, this should have given birth to more complex creatures. Were we to limit ourselves to that point of view, our problem would indeed be insoluble. The problem is: why did cell life appear at all? For it is precisely cells that *are* life. It would be the worst kind of self-delusion first to declare that your living creature is a system endowed with a power for servo-mechanism which naturally brings about growth, then to declare in authoritarian fashion that this power is *a priori* " inherent " in the cell.

The considerations of the preceding chapter all go to suggest that the key stage in the history of life is its very beginning. What we need to do is: discover what process it was that produced a form of matter essentially capable of self-reproduction. In our

initial outline of the standard panoramic account of the development of life (but going back only 1,000 m. years), the reader may have had difficulty in avoiding the uncomfortable feeling of starting a thriller film in the middle. The fact that we missed the opening sequence makes everything else enigmatic. Indeed, if it is a cinema which shows a continuous programme, one burns with impatience while waiting for the particular film to start again and reveal the wretched beginning.

Now, at that very remote epoch where we begin to be aware of consequences of the initiation of life—in the shape of those early unicellular forms—there is no doubt about it, the initial act of life has been " committed " long since. We realise, if we look at the situation at all objectively, that those early unicellular living things, which by our standards of today are most elementary, were in fact really the end-point of a first sequence which was very long drawn out. We need merely consider the little amoeba, classically cited as model of the most simple form of life. Of course, if we compare our amoeba to a modern mammal, or even merely to a fish, it looks a miserable little thing, only 0·2 millimetres in diameter (about 8-thousandths of an inch). We feel it to be a formless little thing, without any power over the world, a creature devoid of interest. We merely allow this minute assemblage of matter to be described as living because it feeds itself, it moves about, it breathes—and it reproduces itself.

But not so fast! Have we really the right to pronounce the amoeba, even the single-celled amoeba, simple? No, not in the least. Even leaving aside the glaring fact that we have certainly never been able to make one, careful examination reveals that despite its restricted size the amoeba is a real factory all on its own. It comprises very many component parts. There are in it thousands of millions of aggregations, each of tens of thousands of atoms. Nor are those aggregations of atoms just any chance associations. In each of them, they all fit together to make a very precise structure. Nor are the various aggregates of atoms in the amoeba just thrown together pell-mell, like lumps of coal in a cellar. Together, they constitute a system of geared cog-wheels which, though minute, possesses an astonishing organisation, in which one can distinguish a very large number of different operations going on. Indeed, in the cell itself we discover localised

physiological processes which are sometimes quite amazing. Apart from the division by membranes, which everybody now knows, into nucleus and cytoplasm, we have the chondriosomes, which provide for the synthesis of new living matter, the chloroplasts, manufacturing starch, and the flagellae, produced by a centrosome, which are capable of tentative movements and provoke a certain displacement of the cell in space. In a word, we have here a number of specific organs. They are all microscopic in size, but they are amazingly specialised.

In the previous chapter I took pains to emphasise the tremendous difference of scale between our techniques and those of life. If I now insist on this again, I do so for a particular reason. It is to throw into relief how unthinkable it is that this astonishing organisation of the cell organism, relatively so complicated, could ever have appeared all at once, overnight, so to speak, in the childhood of our world. It must have taken a very long time to develop.

What we have just described applies in general to all the protista that we know. Even where unicellular, these things all presuppose a vast preceding process of fine adjustment on the part of the matter of the primitive earth. Far better without more ado face the facts: these minute primitive forms are not the beginning of life. They are the end-point of a first tremendous adventure story: the *terminus ad quem* of the prehistory of life.

This of course is not to forget that beyond this we have to do with a second great adventure, when groups of cells join together to give birth to living creatures which are not only complex but also highly differentiated one from another by a play of fortune which has bequeathed to us the extraordinary diversity of our animal and vegetable worlds. This later epic of living matter was indeed to be more spectacular, accompanied as it was by transformations which are nearer to our own scale of vision. But all these early developments assume a character which is quite magical. Let us not hide the truth: it is still the prehistory of life which is the most exciting thing of all and also the most original. It was then that the real miracle of life took place. It was then that biological mechanisms as such were first established and the amazing laws which later we find working throughout the evolution of all species were codified.

Therefore, let us pore over that extraordinary period anterior to —1,500 m. just as long as proves necessary, and let us insist on logical argument reconstituting that genesis from the real starting-point, that is, from the time when on this globe there was nothing but the raw materials of which all life is composed.

Our first step will be to get to know the actors who occupy the stage in that prologue. That means—the basic atoms, the special fusion of which, in the first compounds, formed matter which was destined by the nature of things to be raised to a new level and become living matter.

FOUR MASTER ELEMENTS

When the curtain goes up on an earth sufficiently cooled, we find two main forms of matter. One is a solid block, made up of the earth's crust, higher parts of this being the land masses, or continents this supports, and a fluid medium, namely the seas and the atmosphere.

Essentially it is the latter which attracts our attention, because it is prone to enter into numerous chemical actions. For we have to bear in mind that the solid part owed its cohesiveness to the existence of an outer network of atoms packed tightly together in crystal structure which literally imprisoned the other solid atoms in its mail, so that they were as if encaged and deprived of practically any liberty. On the contrary, the particles in a fluid, gas or liquid are, however, without this crystalline outer wall, hence they are " free ". In a gas, for instance, all the atoms are constantly flying in all directions, bumping against one another or against any barrier, and at the rate of several thousand million bumps a second. And even in a liquid, where they are less active, the commotion can be particularly vigorous. The particles here have an additional feature. They are linked one to another by forces of attraction which forbid scattering. Though they are not still, their motion is not unlike that of a basketful of crabs. Liquids and gases are neighbouring states which are both characterised by constant movement of the elements which make them up. Indeed, there is no real demarcation line between liquids and gases. That is why, when a liquid has turned into a gas by evaporating, we sometimes call it a vapour.

This means that there was purpose in our classification of the oceans and the atmosphere under one term. We have to count on there being a continual passage of small particles from one state to the other, gases present in the atmosphere dissolving in the oceans and, inversely, water-vapour spreading throughout the atmosphere. The main difference between the two states is one of degree of concentration.

If, however, we turn to consider the chemical make-up of the primitive earth, we are at once struck by one fact: whereas the continents formed a complex mass—what geologists call the magma—in which there was a mixture of almost all the types of atom which exist in the universe, the fluid environment was on the contrary formed almost exclusively of four elements, which seem to merit characterisation as *the fundamentals*. These are: hydrogen, carbon, nitrogen and oxygen. Water, ammonia, methane and carbon dioxide were four common compounds in each of which were certain of these four elements.* Even if we add that apart from hydrogen the early atmosphere of the earth also contained prussic acid, we have to add that this substance too is but a ternary compound, formed of carbon, nitrogen and hydrogen.

In a word, when the curtain goes up, we find four actors on the stage, and these four actors, each of them an element, interact in the most remarkable of plots. It is quite clear, too, that these must be at the basis of organic matter.

THE COMMON LOT

Now a digression, to get this phenomenon in its right place in the universe. The question is inevitable: why these four elements? Was our Earth privileged, to have had its fluid environment endowed with precisely those atoms which made possible the most remarkable chemical structures?

* Water is composed of two atoms of hydrogen, one of oxygen: H_2O
Ammonia is composed of three atoms of hydrogen, one of nitrogen: NH_3
Methane is composed of four atoms of hydrogen, one of carbon: CH_4
Carbon dioxide is composed of two atoms of oxygen, one of carbon: C_2O
Hydrogen cyanide (prussic acid) is composed of one atom of carbon, one of nitrogen and one of hydrogen: HCN
Also see Plate II, facing page 97.

The answer is: No. It was the common lot, for with these four, hydrogen, carbon, nitrogen and oxygen, we have the four elements of which there is widest distribution throughout the universe. This we can confidently assert, for modern techniques, starting from the analysis of cosmic rays, have furnished us with pretty precise pointers as to the quantities of the various elements that make up the vast universe. In this matter we find a remarkable universal uniformity, of which, indeed, atomic physics have known how to make good use.

Generally speaking, the matter of the universe consists of:

(1) the gases hydrogen and helium, hydrogen being the greater part, the helium merely the residue of natural nuclear combustion of hydrogen;
(2) the carbon-oxygen-nitrogen series.*

Our globe, of course, obtained its share of these four most common elements in its fluid environment. This is easily understandable. These fundamental atoms happen to be light. They are also able to combine together, giving rise to compounds which at ordinary temperatures are liquid or gaseous. When the temperature of the Earth had fallen to one still of some thousands of degrees, hydrogen and oxygen combined to form molecules of water. At a temperature of 1,500° C. the fraction which did not thus combine was less than one-hundredth of the total. Similarly, carbon and hydrogen produced methane, and nitrogen and hydrogen produced ammonia and hence these compounds were once part of the initial atmosphere of the Earth.

So far, then, everything is logical. An explanation of the same

* We may observe in passing that it is striking that these elements also happen to be the very basis of the " mechanism " of the stars. We must bear in mind here that in the stars we have enormous temperatures, reaching millions of degrees. This prevents the atoms uniting, to produce substances. Indeed, the nuclear reactions which do take place result not from normal combination of atom and atom, but from interreaction between the nuclei of atoms. Just now we referred to the basic nuclear combustion. This is the cause of the energy radiated by the stars and the transformation of hydrogen into helium. By a theory known as "Bethe's cycle", it is widely believed that we have here a cycle of transformation in which carbon, nitrogen and oxygen play successive roles. In a word, even the " life " of the stars is based on these same four elements—hydrogen, carbon, nitrogen and oxygen.

order shows why most of the gases thus formed were retained by the Earth for thousands of millions of years, rather than being dissipated in space. We need to say " most of the gases " because, in view of the enormous initial quantity of it, it is very likely that apart from these compounds, there was still a very large amount of this gas in the initial atmosphere of the Earth. If, however, one examines the possibility of the escape of gases from the field of gravity—the pull—of a planet, it is easy to show that the chance of such escape is inversely proportionate to the mass of the planet and that it is the lightest gases which are most affected (particularly if at very high temperatures). Now, the relative mass of the gaseous molecules which interest us (for water was still " water-vapour " or gas) are the following:

Hydrogen	— 2
Helium	— 4
Methane	— 16
Ammonia	— 17
Water	— 18

In other words, it is hydrogen and helium which qualify as " very light gases " likely to be lost, while methane, ammonia and water-vapour (i.e., water in a gaseous state) as heavier gases, were much more likely to be retained. They therefore now preponderated in the fluid medium of the early Earth.

It is interesting here to glance comparatively at the evolution of three typical heavenly bodies. That enormous planet, Jupiter, comprises today practically all the initial constituents, in particular, an atmosphere containing hydrogen. We should, however, note that on Jupiter, on account of its low temperature (it is far distant from the sun), the methane is liquid. On Jupiter it constitutes the " oceans ".

Our own globe, being a planet of intermediate size, has suffered a steady loss of its atmospheric hydrogen and helium, but the heavier gases have been retained. As helium does not enter into any chemical combination, it has been lost. Hydrogen, on the contrary, has been retained, because it early entered into feasible compounds—water, methane, ammonia.

A very small globe, like our own moon, on the other hand, had too feeble a mass to retain its initial fluid. Hence today it is no

more than an arid mass of rock, equally lacking atmosphere and oceans.

The result was that our Earth, originally acquiring the " normal " atoms of the universe, retained a fluid wrapping essentially because of two factors: its relative mass and its distance from the sun. Any planet with a similar mass and a similar distance from a star like the sun should have a fluid environment like our own.

In this respect, in our own solar system, it is only Mars and Venus that come into consideration at all, though even so there are important differences to note, such as the absence of a cycle of night and day on Venus and the existence on Mars of a much rarer atmosphere, by reason of the planet's lighter mass. Indeed, to find at all close resemblance to the Earth, we should have to consider some other planetary system. Such must exist in the universe, and in great numbers. Our galaxy alone numbers tens of thousands of suns, and whatever is said about the proportion of these which have systems of planets turning about them, it is at least a tenable hypothesis that there are quite a large number of planets which happen to have the same conditions as our own. Unfortunately, we have so far not had any means of identifying such pseudo-Earths, if for no other reason because of the stupendous distances between them and us.

But we are investigating not planets like our own but the origin of life on this earth we know. First, however, we must say flatly that it is mistaken to imagine that life could start up from any combination of elements. I am highly critical of the tendency to imagine the appearance of life on other worlds starting from totally different chemical elements. Writers of certain romances about this have given far too free a rein to their imaginations. It has been emphasised before—and needs re-emphasising again—without carbon we have no living matter. Generally speaking, we can state confidently that our group of four principal elements, carbon-hydrogen-oxygen-nitrogen, is absolutely essential to life. On the other hand, though this is so, that is no reason for assuming either that the presence of those elements on this Earth is our exclusive privilege, or that any other planet which might have—or has had—the same conditions as ours has automatically assumed the same features.

AN END WHICH WAS A BEGINNING

We thus start off with a *mise en scène* which itself was a logical development. For reasons which we have just examined, our earth about —1,500 m. possessed a fluid wrapping which consisted essentially of the four principal elements combined as water, ammonia and methane.

The water now constituted the immense mass of the oceans. A small part, however, was in the atmosphere, in a state of vapour. The quantity of water-vapour in the air today is such that, were it to condense, it would raise the level of the oceans by only about six inches. But in the primitive atmosphere there was very much more water, by reason of the temperature being so much higher. For the same reason, there was a great deal of methane and still more of ammonia dissolved in the oceans. There may also already have been some carbon dioxide, which would be distributed between ocean and atmosphere, in the proportion of 97 to 3.

So much for the setting. One might well imagine that this would have ended the matter. At least, one would say that though, under the influence of differences of temperature and various purely physical forces one might expect a more or less intense physical commotion, there still seemed no reason why these constituents should change their nature and give rise to other substances.

However, matters did not rest there. The reason was that these initial substances were liable to chemical interactions. After all, just contemplate this initial situation. What have we? There are countless molecules of water, methane and ammonia roving wildly in all directions. They frequently collide. Was there no likelihood of such collisions breaking any of them up, and the resultant fragments re-combining in some other manner? Yes, this was theoretically possible. Moreover *it was bound to follow* if the medium were " agitated " sufficiently, that is to say, if it were to be energised by being subjected to such a thing as a radiation capable of lending some of the particles present the necessary energy to break them up and then to bring their fragments together into some other combination—supposing, of course, such " something else " was feasible.

This is precisely what did happen. The initial atmosphere was

in fact disturbed, " energised ", and by several sorts of energy. Dauvillier and Desguins, who some time ago made the most valuable contribution we have had to the solution of the problem of the conditions in which life began, have listed four principal energy sources: sunlight, atmospheric electricity, radio-activity and the heat of the earth's core. The first two were certainly sources of considerable potential.

Every ten square feet of the earth's surface exposed to ordinary solar radiation indeed receives a force of 2 h.p., which in the course of geological time did after all add up to a tremendous amount of energy. But do not let ourselves be carried away. This figure represents the sun's *total* radiation. The utilisable figure is only that part of the energy which comes in the short waveband. That alone can instigate chemical action. The sun, however, radiates most of its energy in the yellow band, that is, where the wavelength is 0·6 microns.* The waves which interest us happen to be in the violet and ultra-violet bands. In point of fact, ammonia hardly absorbs any energy radiated at frequencies below 0·24 microns, while for the other constituents we should need still lower values, namely 0·18 for water, 0·14 for methane and 0·09 for hydrogen.

The real problem thus is the amount of energy radiated by the sun under a wavelength which we may fix at 0·14 microns (we shall soon see that the case of hydrogen is of secondary importance anyway). Now, is the amount of such energy radiated appreciable? Well, the fact is that although it is still far from negligible, it does not amount to more than a ten-millionth part of the total solar radiation. Here one needs above all to keep in mind a very important detail: today, at a height of some eighteen miles, our planet possesses a layer of ozone in the atmosphere which absorbs a considerable amount of solar energy. That layer, a by-product of atmospheric oxygen, did not exist in the period we are now considering, for the simple reason that the earth did not dispose of any free oxygen to form it. In other words, the intensity of the ultra-violet solar radiation which reached the earth at —1,500 m. years was much greater than that of our time.

* Micron: a micron is 10^{-6} m. (i.e., $\frac{1}{1{,}000{,}000}$ m.) i.e., one-millionth of a metre (approx. of a yard),—about 28 microns equal " one thou ".

Next, atmospheric electricity is also a source of energy worth considering. And, curiously enough, quite by coincidence, the amount of energy which we find the earth receives annually from lightning happens to be equal to the solar radiation of below 0·14 microns. Here we also need to take account of two other important factors. First, it is likely that in the early stage of our earth there was more atmospheric electricity than today. Further, though the intensity of solar radiation dwindles right away when one comes to consider shorter and shorter wavelengths, the output of energy in the ultra-violet band is markedly increased as soon as an electric discharge begins.

In short, we may assume the existence on the earth, in the initial phase, of radiation which might well have a chemical action on the constituents of the earth's fluid wrapping. The intensity of such radiation or the weight to be given to one source or other of energy is open to debate, but without really affecting our conclusions, for the limits of discussion are too insignificant to have any appreciable effect. We may note here that for a long time opinion veered to the side of sunlight as the explanation of the formation of organic molecules, for the reason that the molecules which enter into the composition of living matter are all dissymmetrical in the same direction, and light which was circularly "polarised" seemed likely to have caused this. This argument is not absolutely decisive, however, for today we know that certain substances also have the faculty of synthesising only asymmetrical bodies of the same type.

CHEMICAL MECCANO

Given the energising, what, *a priori*, could then take place? We have our molecules of ammonia, methane or water-vapour broken up into atoms—or groups of atoms—which are capable of re-combining into other combinations, these further being capable of joining up with certain primitive aggregations, to give rise to more and more complex structures. What is the result of this process?

No, let the reader not worry, we have no intention of imposing an austere course of any sort of chemistry on him. We merely wish to point out that the atoms are intrinsically pieces in a sort of meccano set. The basic rules for joining them (what can be

joined to what, and in what proportions, and so forth) are very simple. The carbon atom plays a key part in it. Apart from this elementary information, we shall do no more than give a schematic glance at the matter. We have merely to state that a series of atoms can link together to build a sort of chain of atoms if the following conditions are observed:

(1) Every atom in the chain must have at least two linking arms —the chemists call these " valencies "—just like a chain of dancing children, which can be indefinitely extended so long as each one has two hands to grip other hands. A single one-armed player would bring a chain to an end, irremediably. Hydrogen happens to be just such a one-armed player. Hence, thus being essentially " monovalent ", it cannot join hands in any chain, except at one or other end.

(If hydrogen has only one arm, the other three principal players all have more than one.)

(2) An atom of a metal can only join hands with an atom of a non-metal. Since both oxygen and carbon are non-metals, it follows that without the help of some other atom they cannot give rise to long chains. Carbon, however, makes up for this shortcoming of two of its fellows. It can play a great part, for it is both metal and non-metal. That is to say, carbon will in a most versatile manner unite with any other element, whether this is metal or non-metal. Even by itself, it is capable of giving rise to chains almost as long as you like.

Apart from being indifferent about its partners, it has four " arms "—four valencies. As well as taking on any other element, it can join hands with itself, or link up with another atom of carbon, using two arms each, each atom leaving two others free, either to join with an atom of oxygen (two valencies) or to be the starting-point of more or less complex side ramifications.

We thus have the following position. Whereas in chemistry, under normal conditions, an assemblage of elements would be able to give rise to only a very limited number of substances, particularly if we had only the hydrogen-oxygen-nitrogen group to deal with, conditions change completely the moment carbon comes on the scene. With hydrogen, oxygen, nitrogen *and* carbon, the number of combinations is to all intents unlimited. This is why the study of carbon compounds constitutes a separate field of chemistry by

itself.* This is indeed what we call organic chemistry. It already lists some hundred of thousands of substances, though the number of possible combinations is immeasurably greater.

All this being the case, if we energise the constituents of the earth's early atmosphere, are we likely to see the production of a fantastic number of the most varied substances? Or is that energising likely to produce only certain precise substances?

RECONSTITUTION OF THE ARCHAEAN SET-UP

Yes, what does then happen? Perhaps our question had better be put: what *did* happen, more than 2,000 m. years ago, when our world was still enveloped in a fluid medium composed of only a small number of elementary substances?

While the reader with considerable interest awaits the answer to that one I am sure he cannot refrain from a sidelong glance at the composition of living matter. A new question at once arises: which of all the many theoretically possible combinations of carbon, hydrogen, oxygen and nitrogen come into the picture? Which of them happened to be on the line indicated for the appearance of living matter?

Now, as any manual of biology indicates, living matter consists essentially of carbohydrates, lipoids and proteins. The two first substances, perhaps better known as the "sugars" and the "fats", are ternary compounds (compounds of three elements) consisting of carbon, oxygen and hydrogen. They may be

* Carbon is a very intriguing element. All elements are basically formed (perhaps "caused by") rare points of negatively charged "electrification" whirling in a number of layers round a minute compact "positively charged" nucleus, but carbon's set of "outer coats" of "negative electricity" is a very balanced or "complete" or "stable" one. It is this that makes the element so versatile, able to be both metal and non-metal. Further, the directions in which its four normal "arms" are extended make it a key element. It cannot be properly depicted on paper. The arms do not extend in the form of a cross, for they are not at angles to each other which are in a single plane. They project outwards from the atom as if aiming from the centre at the equidistant points of a regular tetrahedron (a body formed of four triangular faces each of which has all its sides equal). The carbon atom is the perfect "rallying centre" for complicated compounds with other atoms, even in its simplest relationships, and when it is added that it has more complex ways too of joining up with other atoms (for nature is very intricate) it will be clear that carbon is indeed the great juggler of matter.

considered as the "combustibles" of the living machine, while the proteins, which are composed at least of carbon, hydrogen, oxygen and nitrogen, are "noble" substances, the machine-parts of life. The names of some of them, such as albumin and gelatine, are household words. The list also includes keratin, the structural stuff of hair and nails, the haemoglobin of our blood, the casein of milk and vitellin of egg-yolk, the myosine of muscles, and so on. The list could be added to indefinitely. In practice all the specific materials which make up the structure of living creatures are always proteins.

In passing we may also note that they too can also be combustible. Another point is that the more improved a living creature is, the higher a proportion of such proteins it contains. Thus in plants, which though living are stationary engines, we find scarcely 2 per cent. protein, together with 20 per cent. carbohydrates, whereas in animals, whose activities require numerous pieces of machinery and a complex system of servo-controls, we find on the average 17 per cent. protein and only 1 per cent. carbohydrate.

In short, we may summarise it like this: proteins are important substances, formed from molecules which are highly organised, and their action is responsible for the working of the living factory.

Indeed, proteins are so highly organised, so complex, that for a long time chemists were in despair in their efforts to discern their structure. Indeed, till quite recently, they were not able to find out much more about them than that they were essentially *quaternary*, consisting of four atoms—our old principals, carbon, hydrogen, oxygen and nitrogen. It has only been the application of recent methods of analysis (to which we shall have to make frequent reference) that has enabled us even to ask the right questions about them. Now it has been shown that proteins are not simply composed of these four elements put together just anyhow. They are very specific structures of these elements already put together in smaller units, which, moreover, can be found in a free state. We call these precise combinations, these "prefabricated" units of the four atoms which, put together, make proteins, the *amino-acids*, because they contain the group of two hydrogen atoms and one of nitrogen (NH_2) which is part of the ammonia group (NH_3).

This is a really great discovery of modern chemistry. The true nature of the proteins is not that they are simply compounds of carbon, hydrogen, oxygen and nitrogen atoms. They are compounds of amino-acids which are themselves definite compounds of these four elements. Proteins are either simple chains of amino-acids linked together, one after the other, or else combinations of such chains, when they are known as polypeptides. The fundamental constituent of living matter thus turns out to be not this and that atom, but this and that amino-acid.*

But let us not leap too far ahead. On our primitive earth we are still faced with an initial environment composed essentially of water, methane and ammonia. Our problem is still that of finding out what will take place when that environment is energised by short-wave radiation.

It might seem that this is a question which could easily be answered simply by making the experiment, that is to say, by setting up in the laboratory a closed vessel containing a gas of the same composition as the earth's initial atmosphere, and either irradiating this with ultra-violet rays or submitting it to an electrical discharge. There are, however, certain purely practical difficulties in the way, and it has only been in the last few years that such experiments have been systematically realised.

True, very interesting experiments were put on record much

* The question has been asked whether we have any right to assume that in the first ages of life creatures were really built of the same chemical matter that they are today. Do we not lack direct knowledge of them? Fossilised examples of the earliest creatures were indeed for a long time supposed merely to offer us " inorganic " information. What was meant by this was that their remains consisted exclusively of hard materials (shells, bones) which told us nothing about the flesh of the creatures or their essential organs.

That situation, however, no longer obtains, and the issue is to be seen from a new angle. Working on 300 m. years old fossils (*Stegasaurus stenops*) at the Washington Carnegie Institute's Geophysical Laboratory, Dr. Philip H. Abelson has recently succeeded in revealing vestiges of amino-acids, thereby justifying his own earlier theoretical conclusions, by which more than 1,000 m. years are required for such an amino-acid as alanine to dissociate at ordinary temperatures. Other amino-acids are also very stable. Glutamine, glycine, isoleucine, proline and valine are examples.

In short, it is no longer reasonable to doubt that throughout its whole history life has been built on amino-acids. It therefore seems equally reasonable to rely on our reconstitution of the basic chemical constitution of primitive forms of life. Dr. Abelson, for instance, has recently subjected a fossil clam shell (*Mercenaria mercenaria*) to quantitative analysis.

earlier. Most notable were those of Slosse, working at Brussels. In 1898 he succeeded in synthesising sugars by submitting a mixture of hydrogen and carbon monoxide for some hours to an electrical discharge. There was also the work of Berthelot and Gaudechon, who produced organic substances, starting with a mixture of ammonia, carbon dioxide and water, while Loeb made attempts to get still closer to the true conditions of the earth in its primitive phase. Further, basing themselves on this work and on weighty theoretical considerations, Dauvillier and Desguins in 1938 evolved a celebrated theory in which they tried to explain, if not exactly the genesis of life itself, at least the process of appearance of substances which would later on be found to be part of the system of living matter.

THE MIRACLE OF CHROMATOGRAPHY

All the same, it was not till 1954 that any laboratory in the world included in its programme a decisive experiment recreating the precise conditions of the Archaean period in a decisive experiment.

To repeat, there were great practical difficulties in the way. For a long time the chemist had certainly been able to assemble the desired gases in a closed chamber. He was also able to submit them to an ultra-violet discharge. That was not the difficulty. The problem was: when he had done this, how was he going to estimate what had happened? This was especially difficult, since he could presume that very many substances might be produced, all in very, very small quantities. However was he to establish exactly what had been produced?

That was the difficulty, and it is only very recently that a method has been evolved for separating the numerous constituents of a mixture when there is only a minute quantity of any one substance present. The method is that of paper chromatography. It is a sensational technique, devised about ten years ago by Martin and Synge, whose great merit it was to grasp how immensely important it was to find means of utilising a phenomenon previously known as a practical analytical procedure. For it was as far back as the turn of the twentieth century that Tswett had made use of the phenomena of absorption and capillarity to separate a number of

organic substances. Chromatography today is to biological chemistry what the telescope is to astronomy. In the years which lie before us, there can be no question, the centre of gravity of scientific exploration will move into the sphere of biology. The importance of the chromatographic method of analysis cannot possibly be exaggerated. The first half of the twentieth century stands under the sign of atomic physics, and (though other discoveries are of course feasible) other domains of science have been systematically investigated. There is, however, no doubt that it is now biology that offers the scientific mind immense uncharted regions. It is the exploration of these that is bound to be the great work of the second half of the century, and that work will move in the direction which I now propose to outline.

The chromatographic method of analysis is important because it enables us to identify every one of dozens of substances in a mixture. It works even if the amounts present do not exceed the mere fraction of a gramme. The procedure is eminently simple. The analyst merely suspends a strip of filter paper in the solution to be examined, and, just as ordinary blotting-paper forms a series of concentric rings of different shades round any point that touches a mixed liquid, the various substances in the mixture to be analysed all trace their own individual paths, according to their nature. (See Frontispiece, also see Fig. 3).

In practice, the analyst works on two dimensions of the paper, dipping two edges at right-angles to each other, one after the other, in two different solutions of the mixture to be analysed. The various constituents form blots, which are brought out by means of a staining developer. The profile of each colour of the blot gives automatic information on the nature of the constituent responsible, since the path of any given substance in a given solvent is known from previous experiment. The amount (the mass) of the particular constituent is also indicated by the area of the blot, the mass being an exponential function of the surface area.

Chromatography has already shown itself to be eminently efficient. One prominent set of results has been the determination by it of the exact structure of a number of proteins. And chromatography was also the method of analysis which made Miller's crucial experiment possible.

MILLER'S EXPERIMENT

The problem was, by means of ultra-violet radiation, to energise a mixture of gases in a closed chamber which simulated the composition and physical conditions of the primitive atmosphere of the earth. To start with, the American scientist rejected ordinary ultra-violet radiation tubes. He needed a wavelength of the order of 0·15 microns, and this would have ruled out observation windows of glass or even quartz. Besides, complicated apparatus would have been necessary to prevent the radicals created forming compounds which might cloud the observation window. Miller therefore decided to produce his radiation inside the chamber by means of an electrical discharge.

To this end, he built up an apparatus consisting of a five-litre flask above a condensation chamber. This furnished him with a closed circuit for his fluid, the flow being at the rate of a few cubic centimetres per second. In his first experiments the flask was filled with a gaseous mixture—methane, ammonia and hydrogen—respectively at pressures of 20, 20 and 10 centimetres of mercury. Water was also introduced. The amount of vaporisation of the water of the experiment resulted in a total pressure of about one atmosphere. The energisation was assured by tungsten electrodes, with a Tesla coil to produce a series of sparks, after the fashion of those of an internal combustion engine's plugs.

Miller left the apparatus to function continuously for a week. He then subjected the product to systematic chromatographic analysis. The exciting result was the discovery that about one gramme total mass of organic products had been synthesised. Among these, amino-acids occupied an important part! More than ten of these substances were identified chromatographically. Glycocoll and alanine took the lion's share, with 4 per cent. and 3·2 per cent. of the total respectively.

Miller's experiment was most instructive. It taught us that out of all the thousands, or rather, out of the millions of possible products formed under the action of periodic electrical discharge, the amino-acids predominated.

Was the result perhaps a chance one? Should one not suspect that with a slight change in the conditions, the results would be quite different? To see whether this was so, Miller set up a

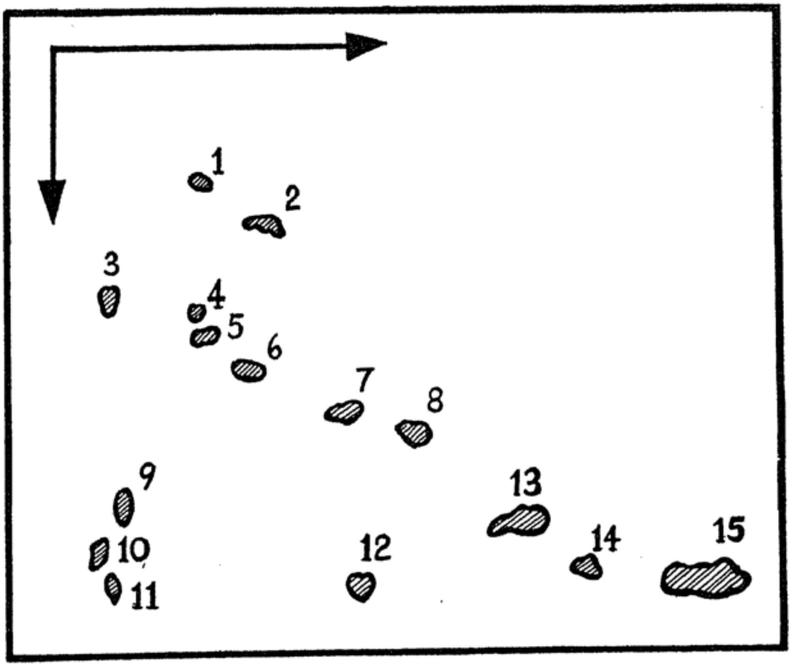

FIG. 3. AN INSULIN CHROMATOGRAM

Diagrammatic representation of a chromatograph of an insulin. (A drop of insulin dissolved in a suitable solvent is placed on the filter-paper at one corner. The various constituent parts separate out and move specific distances from their starting point. This operation is repeated with another solvent in a direction at right-angles to the first. This again separates the constituent parts of the substance—in this case, insulin—so that they are well spread out and differentiation is easier.

Key:

1. Aspartic Acid	2. Glutamic Acid	3. Cystine
4. Serine	5. Glycine	6. Threonine
7. Alanine	8. Tyrosine	9. Histidine
10. Lysine	11. Arginine	12. Proline
13. Valine	14. Phenylalanine	15. Leucine and isoleucine

second apparatus, slighty different from the first, with a much more rapid circulation of the fluid. The results were substantially the same. The speed of circulation had little influence on the result.

Miller then decided to try a totally different method of energisation. He worked without built-in electrodes. Instead, he placed the flask between the electrodes of a condenser. The product of

synthesis in this case was not so abundant, but the over-all result was identical. Repeating his experiment, Miller every time obtained synthesis of amino-acids, with glycine and alanine most frequently the principal products. Only on one occasion did sarcosine take first place.

There were, however, still objections to be made. For instance, there was the question of hydrogen. Miller had introduced hydrogen into his flask. Now, though the earth's atmosphere certainly started off containing hydrogen, we have noted that this must have been dispersed rather rapidly. It is therefore not certain that hydrogen could have played an important chemical role over a long period. A number of experiments were therefore made without any free hydrogen in the flask at the outset, but the result was substantially the same. It was soon shown that it was not necessary to add any hydrogen at all for the experiment to succeed. The reason for this was that as the organic compounds were synthesised, a supply of free hydrogen was produced from the initial constituents containing hydrogen.

Though the principal interest of Miller's experiments was the bare fact that any amino-acids at all were synthesised, it was also instructive to see which particular ones were made. Interesting facts emerged, such as why only the chromatographic method of analysis offered a technique which could satisfy the requirements. Apart from a range of secondary substances which were not the subject of inquiry, what one mainly found in the result, though their proportions varied strikingly according to the conditions, were precisely substances particularly useful in the life process.

For instance, substituting a condenser for electrodes, the over-all proportion of the amino-acids was considerably reduced, but, on the other hand, there were more hydrocarbons. This new experiment produced a quantity of formic acid (7 per cent.), together with acetic, propionic, glycollic and lactic acids. Cyanic acid and some aldehydes were also formed.

True, we still do not know whether all these products are formed in the gaseous stage by the combination of radicals and ions which the electrical discharge liberates, or whether only a certain number appear at this stage (principally volatile acids and aldehydes), the others being formed later, in the solution. This, however, is a secondary consideration. What is of great interest,

however, is that in Miller's experiment we also have the formation of carbon dioxide, carbon monoxide and free nitrogen. Hence it is now irrelevant whether or not the initial atmosphere of the earth contained carbon dioxide, for this gas is clearly produced as soon as the first organic compounds are made.

The importance of the formation of carbon monoxide will be realised if the reader recalls Slosse's early experiments in the synthesis of sugars from carbon monoxide and hydrogen. Indeed, speaking in general terms, we can say that we have almost too many possibilities of explaining the birth of the saccharides, the more so since, as Berthelet showed, formic aldehyde permits the formation of numerous hydrates of carbon, as well as of hydrocarbons resulting from polymerisation.

In other words, Miller's experiments teach us that the energisation of a gas of probably the same composition as the initial atmosphere of the earth "naturally" produces the notorious amino-acids, the formation of which had previously so worried biologists, and also fats, saccharides, hydrocarbons and other substances.

Now, these were such sensational results that before finally accepting them one needed to be quite sure that the experiments were not rendered invalid by some major error. For instance, suppose the apparatus had not been perfectly clean! Was there not a danger of the amino-acids having been synthesised by micro-organisms?

To answer this, the experiment was repeated in every respect except that it was done without any energisation. The production of amino-acids was now less than ten-thousandths of a gramme, that is to say, less than the ten-thousandth part of the previous result. Was this conclusive proof?

Not quite. It was still feasible that the part played by the electrical discharge was to provoke the appearance not of amino-acids but of simpler substances, these subsequently being transformed into amino-acids by micro-organisms.

Resort was therefore had to yet another experiment. In this, the first step was to keep the apparatus in an autoclave for eighteen hours at 130° C., and only then, with all possible precautions taken, repeat the previous experiment. The production of amino-acids was now exactly the same as it had been without the

autoclave stage. This meant that the intervention of micro-organisms was satisfactorily disproved. The amino-acids had definitely been synthesised *by the electrical discharge.*

Admittedly, we cannot state categorically that these syntheses reproduced the conditions of the primitive earth with absolute faithfulness, be it only because we can never know exactly what atmospheric pressures existed at that remote time. The wide range of conditions provided by Miller certainly does seem to have covered all the conditions which must have prevailed on the earth in that initial epoch. But that is really not the main problem. This is that the interesting fact which emerged from the experiments was that there was this systematic tendency of the constituents of the primitive world to persist in furnishing a high proportion of amino-acids.

It remains to go into one more point. If we estimate the energy expended in Miller's experiment, we find that values of the order of 1·5 m. calories are required to synthesise one gramme of organic matter when sparks are used, and ten times more power is required when we only make use of an electrical field. The production was indeed a poor one quantitatively. But there is nothing whatever to suggest that the early earth did any better. It is certainly of interest to have some suggestion of an order of magnitude for the rapidity with which amino-acids are synthesised by natural forces.

If now we place ourselves in the most unfavourable of conditions, and admit amino-acid production even poorer than that obtained by Miller, it is still clear that natural forces operating over the whole oceanic expanse of the globe (or, at least, over a large zone of this about the Equator) could in every million years have synthesised organic substances to a depth of several millimetres. Or, at least, we can conclude that the initial step took place at about this speed, till the density of amino matter was sufficient to give rise to totally new processes of organic synthesis.

THE AMINO-ACIDS

Let us, however, now look a little more closely at these important substances, the amino-acids, whose biological role, after all, has only really been realised in recent years.

What are they? Certainly not much to look at. They form a

small family of substances practically unknown to the non-specialist. They are endowed with outlandish names, which scarcely favours popularity. The simplest, which we have already mentioned, is glycine or glycocoll, also known as amino-acetic acid.* It is comparatively easy to prepare, by the action of sulphuric acid on glue or gelatine. At least, that is how Braconnot discovered it in 1820. It proved to be a solid white substance, soluble in water, sweet in taste. These are also properties of the other members of the family, of which there are about twenty-five altogether. Among the more important, after glycocoll, we may mention alanine, the amino-acid which is particularly common in proteins, valine, leucine (which constitutes more than 30 per cent. of the globin part of haemoglobin) and glutamic acid, which constitutes 40 per cent. of gliadin, the proteid of wheat.

The next thing to notice is that amino-acids *de rigueur* embody at least the four fundamental elements, carbon, hydrogen, oxygen, and nitrogen, while some also comprise sulphur—such as cystine and cysteine, the latter substance being an acid present in the bile. It goes without saying that none of these latter were synthesised in Miller's experiment, because his flask did not contain any substance containing sulphur. If, however, we were to imitate the conditions of the primitive world to the last detail, we should be obliged to alter the experiment slightly. Realising that though the primal fluid consisted preponderantly of the four main elements (or substances formed from them), other elements, however rare, may have also been present: This was notably the case with sulphur. There was also some phosphorus, and that element occupies an important position in the nucleoproteins. After all, the primitive oceans contained in solution a number of salts which an exhaustive study would have to take account of.

THE "QUEENS" OF BIOCHEMISTRY

The amino-acids are bodies of great importance in the chemistry of life. The reason is that they are endowed with the privilege of a strange dualism. The reader will surely know that the chemist classifies all substances in relation to a neutral medium (of which

* $CH_3.COOH$ (acetic acid) $NH_2.CH_2.COOH$ (glycocoll or glycine).

by definition water is the model) as either acids and bases. Standard chemical unions take place between acids and bases. But the amino-acids are both acids and bases. This allows them to indulge in a great wealth of reactions. They combine the properties of *both* normal families of substances. When faced with an acid, they behave like bases, and vice versa. In short, they are on the biochemistry board what the queen is on the draughts board. They can go anywhere.

On a higher level still, we can say something else about them: they repeat the prowess of the carbon atom. This, remember, is privileged by its double character of being both metal and non-metal, and can link arms with any other element to produce chains of elements. It can also link arms with itself. Now we find that on another plane the amino-acids are able to do just the same. Being so thoroughly both acids and bases, they too can also unite among themselves. Hence we have the feasibility of chain molecules consisting of strings of amino-acids in precise orders, and experiments tell us that in nature we do in fact find such chains. Proteins may consist of strings of *thousands* of amino-acid molecules!

In itself, admittedly, it is not the fact that amino-acids form chain molecules that singles them out. Merely to form a chain molecule is no longer regarded as anything special. Today, manufacturers of plastic materials regularly fabricate such long molecules.

The way these chain molecules are put together does, however, teach us something. The general scheme is that of the utilisation of an aggregate of atoms constituting a monomer capable of uniting with itself. The structure is directly comparable to the linking of railway wagons one to another, to make trains. In the chemistry of the plastics the trains may consist of hundreds, even thousands of coaches, that is, of monomers (that is, single molecules, a substance formed by fusion of a number of molecules being called a polymer), with the possibility of giant chains, no thicker than 10–20 angstroms, but several tens of thousands of angstroms long. The angstrom, we may add, is the 10-millionth part of a millimetre.

This way in which the amino-acids link up their molecules into chains furnishes us with a totally new situation, by reason

of the enormous number of combinations realisable in such chains. The point is that in classical chemistry—as, for instance, in the plastics industry—the construction of very long chains is a common operation, but here almost invariably this chain structure is that of a single monomer and it is only the number of elements involved in this molecule that gives the substance its character. Even when it is not a case of a single monomer, the shape is merely due to two sorts of monomer being used. This, however, is to admit that we can build up the structure no matter how.

On the other hand, with the amino-acids we find about twenty basic monomers, each able to give rise to countless chains, each of which will be a different substance, the properties of which will vary considerably according to both the nature of the amino-acids from which it is made up and their order.

Perhaps a comparison may be ventured. Let us picture the chain molecules as words, even phrases, made up, of course, of the letters of the alphabet. By stringing the letters together in various orders, we can make all manner of statements. The sense of a statement is often fundamentally changed merely when we change a single letter. In other cases the alteration of a letter merely lends a slightly different shade of meaning to the statement. But the most remarkable thing about our amino-alphabet is the eloquence it allows us. If we take the round number of only twenty principal amino-acids, and confine ourselves to a " phrase " containing only nine of these, we find we can make no less than 512,000 m. different statements! And when one remembers the point made above, that these chains of amino-acids may number hundreds of " letters ", all linked together, and that in addition to the simple chain we can in fact also have other methods of linkage (" bridges " can be thrown across, to join two chains together), it will be clear that the number of compounds theoretically possible to be made from these amino-acids staggers the imagination. The " phrases " we can make far exceed in number the total number of atoms in the universe.

Here we have come upon a predominating feature of the chemistry of life. The number of conceivable structures made from a given number of constituents is stupendous. Moreover, to a cybernetician it is obvious that the members of any such family of substances must each have embodied in it a vast amount of

"information". For instance, imagine chains of 1,000 amino-acids each. We could have some 400 m. of them, all identical except in two small points only. Everywhere else in the 400 m. examples of the chain, the set-up would be exactly identical. This offers the feasibility of innumerable minute differences developing between substances which over-all, in 999 points out of 1,000, have exactly the same structure.

The amino-acids, in fact, constitute a new chemistry all by themselves, and it is a chemistry of no mean importance, one with its own specific laws. To return to our comparison with letters. Just as we have little likelihood of forming words and phrases making sense when we merely jumble some of our letters together, so likewise, among all the many, many amino-acids theoretically possible, only certain ones prove to be of practical interest. But this is one of the problems to which we shall come later in our study.

For the present, the interesting point that emerges from what we have considered is that from now on the old chemistry is largely "off the map". This indeed is why no attempt has been made to burden our story with an account of the various processes by which the fundamental atoms are joined up. All we need to know—and that is the point we have now reached in our argument—is the essential fact that these amino-acids did form naturally at the very start of things in the fluid medium which covered our earth.

From now on we can assume amino-acids as among the raw materials existing "at the outset", or at least, before life appeared. On a higher plane we now have to consider how these new "prefabricated" pieces, the complex, versatile amino-acids, joined together. Our four principal atoms turn out to have been only the puppets in a sort of prologue. The early molecules formed from them—water, ammonia, methane, carbon dioxide and so forth—were also only puppets of the prologue. The real actors in the play proper are the amino-acids, and it is their work that we now have to study.

CHAPTER IV

Molecule Machines

AFTER the prologue, the play. As the first act begins, we have a situation in which the constituents of the fluid medium, energised by natural sources, have formed organic compounds of great diversity. These are principally hydrocarbons (later to give rise to the aromatics), sugars and, above all, the notorious amino-acids, which, as we know, are the alphabet out of which the language of proteins is to be formed. All these substances are now brought into action in the life cycle.

So far, however, there *is* no life cycle. All these substances are still merely " chemicals ", initial raw materials, disseminated throughout the waters, and there is no visible machinery by which they may be used. All we can say is that matter has reached a third stage. At the very outset we had those four principal elements, carbon, hydrogen, oxygen and nitrogen. These existed in free form while our globe was still very hot. Then, after a certain measure of cooling, they combined, to form water, ammonia and methane. Next, by the emergence of more complex chemical compounds, headed by the aminos, a portion of them developed up to this third stage.

Seeing the way things have turned out so far, one might conclude that nature had done her work well. But that really only raises a problem about the next stage. Even if, starting with those four elements, we have got these many organic substances, what is there in this fortuitous chemical combination to tell us that we have just what we need for making living matter? It all seems a little too much like the *Swiss Family Robinson's* world. Some students of the matter have therefore tried to be very stern realists. We suggest that the amino-acids are very special substances. They, however, go to the other extreme and assert that there is

nothing special about these chemicals (the amino-acids) at all which distinguishes them from any others. One should, they say, see in them merely so many chemicals, which later are "utilised" by a totally different force, "life". Yes, but is it sensible to blind ourselves thus to the curiously logical way nature has so far worked? For out of countless possibilities, it has produced principally substances which life will, as it turns out, be able to "utilise". The problem—why this was so—is certainly still unanswered. But it does look as if there might possibly be a key in our four initial elements, and indeed we do very soon find one.

The real inquiry begins now we have reached this higher level and have the amino-acids to consider. And we soon perceive a striking feature of their structure, by which, once they existed, they could no more help hooking themselves together into chains than will a case of hooks shaken up together.* All the substances in our initial fluid medium are constantly being mixed together, and as the mixing goes on, they constantly get caught in each other and detached again, yet in the end do tend to stick together in a more or less stable way, in chains. By reason of this feature of the amino-acids, it is difficult not to concede that once one had such a broth of amino-acids, various protein molecules were bound to appear. After all, this is not exactly a new idea. It is now fifty years since Fisher stated the conditions in which two molecules of glycine will get themselves hooked together, and go on getting hooked to others, to form a chain molecule consisting of eighteen amino-acids.

Nevertheless, although natural processes did produce such chains quite logically, this still gives us no inkling how anything else would emerge from it all. Indeed, have we not made a point

* Those who may find this suggestion too fanciful should read the communication made by Professor L. S. Penrose and R. Penrose to *Nature* of June 9th, 1957, bearing on this very subject. These two researchers into genetical problems there describe an experiment with blocks with specially shaped two-dimensional outlines of two kinds which can mortise one into another in various ways. If in a confined space a row of these blocks, together with any particular interlocked combination of two of them, are shaken together, it is found that wherever the same two types of block stand side by side they automatically mortise into each other in the same way as the pattern. It was previously argued that such a mechanical process of self-reproduction, even if conceivable, must be too complex to devise. That objection is now disposed of by this brilliantly conceived experiment and fascinating light is thrown on the mechanical factor in the process of self-reproduction.—*Translator*.

of the infinite variety those chains could assume? This means that, to explain life, we still have to find out what it was that selected certain chains rather than others and subsequently ensured the organisation of the matter thus assembled in such a way that it assumed the astonishing power of further development which we call life. For what certainly does happen is that, starting with a humble molecular agglomeration, this organising principle goes on improving the aggregates of molecules till these at last become plants or animals, entities evolved to the point of being able to do an unbelievable number of things. The problem still is: how this development could arise from chains of amino-acids which were created purely by chance.

THE DISCOVERY OF THE SERVO SYSTEM

Let us recap our argument, to get the situation well in focus. After the vast panorama of the history of life, we first tried to elucidate the "plan" by which the living creature works. We came to the conclusion that living creatures involve a series of servo-mechanisms designed to serve the reproduction of themselves. This led to the suggestion that we might do worse than seek the origins of life in some form of inanimate matter which was capable of exercising some measure of control over its environment.

This was the first stage of our proposals. Next, examining the conditions of our earth in its primitive state, we have now shown that the play of physical and chemical forces gave rise to many substances, but most notably to long molecules formed by chains of amino-acids.

It is here that we may try to throw out a bridge. Suppose we can show that it is precisely these chains of amino-acids which are endowed with that power of servo-control which we have been looking for. Certainly they do behave like "order-establishing machines", inclined to effect certain changes in their environment. Most strikingly, they are able to act on other chains of amino-acids. And in this fact we have the basic servo-mechanism which is at the origin of it all.

But whence this special power in the amino-acids? The answer to this is that it does not seem to be a property reserved to

amino-acids alone. It is valid for any molecule. The great feature of the amino-acid is that it possesses this servo-mechanism power to a very much higher degree by reason of that fact that its own organisation is on a so much higher level. Here is the cardinal fact, too generally ignored: every molecule, every functional association of atoms, is intrinsically a machine capable of exercising a specific action on certain other particles.

Yes, the molecule as such is a machine. It is a machine because it is a structure of atoms with precise architecture. Nor is it a static model. Indeed, in the atomic world of small particles there is not such a thing as a state of rest. Even in the atom, the electrons are constantly in motion about the nucleus and the constituents of the nucleus are also in a state of perpetual agitation. Similarly, the elements of the molecule too are in constant motion. There are electrons moving round in specific regions, or orbitals, while the nuclei vibrate about points of equilibrium, and all this takes place within a framework of fixed numerical constants dependent on the nature of the atoms which make up the molecule and on the way in which these are associated together. This structure gives the molecule its own electric field and its magnetic moment. Most important, it offers us that quality of organisation which we have been looking for. By reason of its vibratory movement, it is capable of influencing its immediate environment, either directly or by its resonance.*

It is a matter for astonishment that for a long time this idea was

* Resonance: since this term is given a very special restricted meaning by some authorities on structural chemistry it is perhaps as well to make quite clear that here it refers to one of the most important of physical phenomena. When energy is emitted intermittently at regular beat, it acts selectively on any adjacent system capable of vibration at that beat. The reason for this is the building up of successive impulses till they attain considerable strength.

When we pull a rope to ring a church bell, and time our pulls to fit the period of swing of the bell, we are bringing our impulses *into resonance* with the hanging of the bell. If a number of metal tongues of various length are mortised into the core of an electro-magnet, and alternating current (i.e., current proceeding in a steady series of short impulses) is passed through the magnet, one of those metal tongues may vibrate, that one which is in resonance with the cycles of the alternating current. If the frequency of the current is changed, the vibrating tongue will cease to vibrate, but any other which is now " in resonance " will begin to do so.

What is striking in such a case is that the vibration does not call for the application of any other force. Another vivid illustration of resonance effect is the vibration which may be imparted to a bridge by soldiers marching. This

practically neglected in chemistry. It was, to say the least, most illogical to have been satisfied merely with knowing the nature of the atoms composing a molecule and their method of linkage. For instance, it is common knowledge that the molecule of water is formed by the union of two atoms of hydrogen with one of oxygen. But how many know that these atoms join arms to form a sort of circumflex accent ^ with an angle of 105°,* while the spread of the arms of it is 1·35 angstroms, with the nucleus of the oxygen atom at the point of the accent, and the nuclei of the two hydrogen atoms at the other extremities. Owing to the movement of the electrons in the molecule, the appearance is rather as if each arm of the circumflex accent half transfixed a peanut at an angle lengthwise, so that the two kernels shared the peak, the region of the oxygen.

Suppose we have here a system which can bring about changes in its immediate environment? By reason of the way its parts are joined together, this molecule consisting of two atoms of hydrogen and one of oxygen is certainly more than the two atoms of hydrogen and the one of oxygen were separately, exactly indeed—in basic principle—as two pieces of metal joined at one end by a bolt are more than two pieces of metal joined by a bolt, for they become pincers.

The crux of it is that when a number of atoms are able to unite they form a whole which is potentially capable of doing something completely new. Here, I think, we have the underlying cause of the

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is why when crossing bridges they may be told to break step. The fracture of certain modern plastic motor-car windscreens offers yet another example. Readers may recall the "mystery" of the screen-shattering which occurred on a certain stretch of the London–Portsmouth road. The reason apparently was that the regular rugosities of the road surface here (caused by the method of laying it) set up a vibration in a number of passing cars which proved to be in resonance with the molecule of the given plastic.

Wave mechanics has given resonance a dominant position in modern physics. It is assumed that every corpuscle of matter has its characteristic vibration period. For instance, in an atomic pile it is by reason of resonance that uranium 235 preferentially absorbs the slower neutrons. Had this not been so, chain reactions with natural uranium would have been impossible.

* This is the figure which Daudel gives in his work on the bearing of wave mechanics on molecular studies. It is also adopted by other authorities, e.g., Louis and Mary Fieser. Ephraim, however, specifies an angle of 104° 31′. These slight variations of calculation do not however affect the principle involved. (See Fig. 4 (page 85) and also Plate II (facing page 97).

servo-mechanisms which we find eventually in the living creature. Even though to understand this may demand something more than the mere principles of physics and chemistry, their origin is to be found in the molecule. Refer back, moreover, to the fundamental consideration which we elucidated above, the conclusion that the servo principle was essentially the creation of order by an agent. This condition is fulfilled by the molecule the moment that it shows itself able to effect the atoms surrounding it without being affected itself.

These reflections prompt further reference to the great error of the customary gulf in our thought between industry and biology. Till quite recently, it was held that the construction of servo-mechanisms required the intervention of a brain. Indeed, this thought may well have occurred to the reader when we suggested the servo-brake as model of servo-mechanisms in general. How could nature—he may have wondered—ever have known how to produce machinery which would achieve so subtle an organisation? Well, here we see that it is achieved quite naturally even at as low a level as molecules, which surely makes it clear why we ought to apply the same language to automation and biology. For biology deals with the world of molecules.

If a comparison which takes account of the work effected by molecules is wanted, polar exploration offers one. Moving in arctic and antarctic regions, explorers know that it is dangerous to talk loudly, because the sonority of the human voice can be sufficient to touch off an avalanche. Thereby if it resonates on a glacier those puny things, molecules, are able to effect tremendous movements.

Here our whole argument began with a molecule of water. But this is a very elementary example of a molecule. With a more complicated one, we can point to a variety of movements in its constituent parts. There are "vibrators" and groups of particles which are in constant rotation. All this movement cannot fail to have some specific action on the molecule's immediate environment. The nature of that action is of course dependent on the structure of the molecule. Here we can speak of a system which on an extremely small scale plays a part resembling that of a machine-tool in a factory. It is capable of modifying or even combining with certain adjacent molecules.

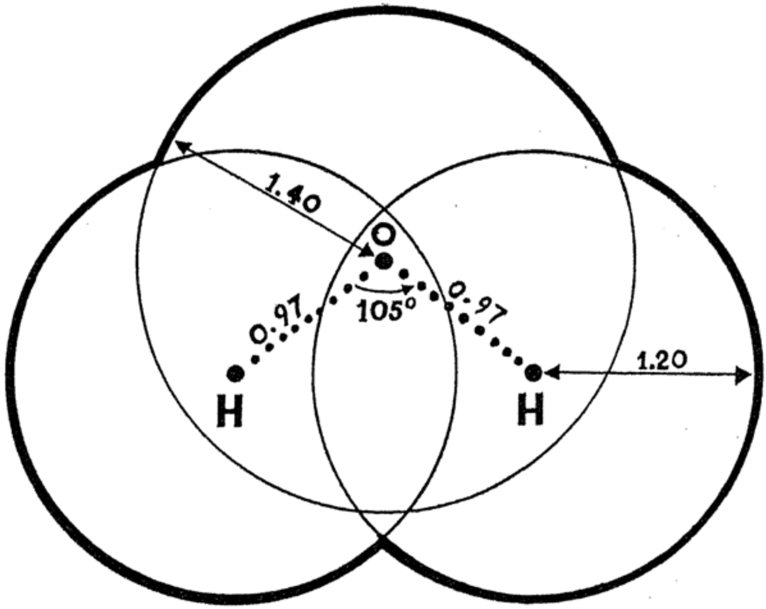


FIG. 4. THE STRUCTURE OF WATER

A schematic diagram of the way in which two atoms of hydrogen and one of oxygen combine at an angle, to form a molecule of water. The axis measurements indicated are in *angstrom units.* $\left(1 \text{ ang.} = \frac{1}{10{,}000{,}000} \text{ mm.}\right)$ All atoms consist of electrons whirling in orbits about a central nucleus. When they combine in molecules there is a complex interlocking or sharing of some electrons. (Also see Plate II, on which atoms are represented by balls. The bottom left-hand combination of three balls represents a molecule of water).

Apart from change of scale, there is of course a great difference between the raw material here and in our industries. With molecules we have the situation, so pregnant with advantages, that the same substance can be both raw material and machine-tool. A chain of amino-acids is a machine able to knot together or unknot or modify another chain of amino-acids, while in turn these others can do the same to other chains, and so on.

This very special aspect of chemistry is fundamentally different from the usual preoccupations of the engineer. When he manufactures a plastic article, he wants it to be transparent, or hard, or perhaps flexible. He is not specially interested in the separate molecules of the material, merely in the properties of them in the mass, when billions of molecules are piled and tangled up in it, to

produce matter on the scale at which we work. In short, the individual character of the molecule does not interest the engineer, and he is quite ready to forget about it.

There is practically only one instance in which the notion of the molecule as machine has hitherto forced itself into the chemist's world. That is in the process of catalysis. We call any substance a catalyst which, when introduced into a mixture, provokes a chemical reaction which otherwise would not take place, and does so without itself playing any detectable part in the reaction. When the reaction is complete, we find the catalyst unchanged.

In some cases the ultimate explanation is simple. We can suppose the catalyst to have combined with one of the elements to produce an intermediate reaction, then by a subsequent reaction to have been restored to its original state. But this will only work as explanation in a limited number of cases. This is why everybody speaks of the effect of " contact " with a catalyst, or says that a certain reaction takes place " in the presence of " a catalyst.

Catalysis was discovered well back in the nineteenth century by Faraday, when he demonstrated the action of sponge platinum on a mixture of hydrogen and oxygen. Before the age of industrial chemistry the phenomenon was to assume considerable importance —for instance, in the synthesis of sulphuric acid or ammonia. Study of the process sometimes revealed astonishing aspects, particularly when it came to distinguishing a class of " anti-catalysts ", for it was found that traces of chlorine or bromine may prevent the hydrogenation of organic bodies. It was, however, in organic chemistry that the use of the phenomenon of catalysts came to enjoy a disconcerting extension. Every textbook, for instance, tells of the catalytic role of *Bacterium aceti* in the manufacture of vinegar or how zymases (extracts of yeast) transform sugars into alcohols.

Is it not clear that we can see in ferments and catalysts, which effect chemical changes without being changed themselves, a molecular machinery capable of effecting a servo operation? It is as if the molecules which exert this power were like tuning-forks moving about in a fluid medium, making given molecular structures resonate when they brush by them. Thereby catalysts impose on other matter certain definite forms of organisation, certain definite transformations.

THE ENZYME

Let us now return to our aggregations of amino-acids. The servo-action has every chance of being more marked with better-organised molecules. Now with certain trains of amino-acids the specificity of the action is very clear. It allows us to distinguish the disproportion of effect characteristic of servo-operations, with distinction between the primary substance, represented by the molecules which act on others, and the secondary substance, which provides the medium on which it acts. The primary substance proves able to " work " on the elements of the secondary with baffling precision. We come upon substances called enzymes, which act in a world in which the phenomena of inertia cease to exist. In a single second one molecule only of an enzyme called catalase can break up tens of millions of molecules of hydrogen peroxide!

There is no doubt about it, this work of breaking up substances by molecules which merely set off or control the process certainly gives us the right to speak of the effectors as machines. The comparison suggests itself of such familiar mechanical devices as those which put the metal caps on beverage bottles as these pass along the line in front of them. There is nothing magical here. It is merely the play of a mechanism on the molecular scale. For we must realise that in this matter of servo-mechanisms all stages are feasible from the case of the molecule which does almost nothing, merely slightly modifying the probability of certain local transformations, up to the case of molecules with a servo-power exercised with the incredible violence of the enzyme catalase, which I have just quoted.

What we need to do now is to bring in the principle of selection adumbrating, at this low level, one of the great laws of life. For let us imagine a cycle started up, with a given medium (which we will call the substratum) under the control of a primary substance which, given the raw material of this substratum, brings about a definite synthesis. It is clear that if into the same medium we introduce another primary substance which acts more rapidly it is very likely that this will use up the substratum for itself. If this second primary substance brings about the same transformation as the first in the same substratum, the result will of course

be quite simply an acceleration of the process. But *if*, on the contrary, it transforms it in some other way, we shall have two distinct actions, one on top of the other, and if the substratum is limited in quantity it is bound to be the more energetic of the two other substances which will use most of it up for itself. It is easy to see—especially if we envisage considerable lengths of time—that it is the strongest servo-actions which tend to dominate the scene.

This gives us a very good hint of the way in which organic matter could develop. For if we take a leap ahead and glance at the role these servo-control mechanisms assume in superior creatures, we are reminded at once that the work of our organisms does basically consist precisely in such chemical servo-actions. This is the case in the work of growth of a living body, for in that process we see molecules humble in themselves subordinating a nutritional medium to organise that raw material into a human being.

Such is the mechanism of action of the substances known as enzymes. They were to play a leading part in the development of life. And yet there was " nothing particular " about them. In classical biology, one called a molecule an enzyme if, in a given medium, it effected a certain transformation. Thus we see enzymes in one case synthesising, in another, on the contrary, destroying substances which, as we have said, may well be other enzymes. *A priori*, what makes an enzyme is the specificity of the reaction which it sets off in a given medium. This specificity is explained by a simple feature of enzyme constitution, an enzyme being unable to work on the molecules of the medium unless there is some agreement between its action and the process required for the transformation of that substratum. This is merely another way of expressing the relationship in industry by which a machine-tool only works on a piece of raw material if this is brought to it. An enzyme likewise has to fit its substratum as a key fits a lock, to use the comparison dear to Fisher and Pauling.

As a matter of fact, the enzymes in our own organism are to be numbered in thousands. Certain enzymes (alcohol dehydrogenase or hydroperoxydase, for instance) control our respiratory mechanism. Others ensure the manufacture of all the substances

the body needs. And we must also realise that there is interaction among the enzymes themselves the moment, by reason of the amazing hierarchy which we discover as soon as we examine the fundamental parts of the living creature, the synthesis of one is provoked by another.

Hormones furnish another sensational example of controls. But whereas hitherto biology has furnished a variety of substances with a variety of names, all of which have had their turn in the headlines (vitamins, hormones and enzymes), biocybernetics invites us to put them all in the same class: that of substances which exercise a specific controlling (servo-mechanistic) action, that action in any case being natural to molecules, but becoming more pronounced as we come to the higher molecules.

Admittedly, enzymes and hormones work in different fields. The role of the hormones is essentially to form the fluids secreted by our glands (hypophysis, thyroid and parathyroid, pancreas, genital, etc.), which as signals are capable of being carried by our vessels all over the body, to exercise a controlling action on definite organs on the lines of action which have already been roughly outlined. Chemically, the hormones are *a priori* much simpler substances than the enzymes. But this only makes their case all the more instructive. It was the hormones which enabled us to bring out the *intrinsic* nature of all these controls.

For a long time it was believed that the substances which entered into the composition of the living creature had a special nature. Later, when chemical analysis showed that they had not, proving them to be put together from the same elements as " ordinary " matter, there appeared a leaning towards the postulation of a mysterious " vital fluid " which permeated organic substances, conferring peculiar properties on them. With the servo-controls now put down to the account of various substances in the living creature, the reader may well ask: is control action due, not to the substances themselves, but merely to their being matter secreted by the living creature?

That this is not so is easily proved. The control action depends solely on the chemical structure of the molecule. A synthetically fabricated molecule has the same action. This has been demonstrated with the synthetic hormones. Indeed, it has been observed that it is enough to build molecules with the same structural scheme

as the hormones for these hormone-like structures, injected into the living body, to control the same organs in the same way, thereby revealing the same physiological properties. As will be realised, this is of the greatest possible interest, for till these proofs there were researchers who held that the controlling character of the molecules in such reactions was not to be imputed to the molecules themselves, but was dependent on their incorporation in living tissues.

The exact structure of several hormones has been determined and their synthesis achieved. As far back as 1901, Takamine and Aldrich isolated adrenalin, and Stolz, three years later, realised its synthesis.* This demonstration, however, was regarded as not entirely convincing, for it was the case of a very simple hormone. It was still asked whether the same similarity of action would appear in the case of more complex hormones formed of chains of amino-acids.

In due course, however, proof of this too was furnished. The American worker Professor Vincent du Vigneaud (who in 1955 was awarded the Nobel Prize for this work, but with whose name one should associate that of Professor Fromageot of France) succeeded both in establishing the chemical composition of oxytocine (a hormone causing uterine contractions in labour) and vasopressine (another hormone, which controls bladder secretions and contracts the blood-vessels) and also in synthesising them. In every case where they have been tried, the artificial hormones have produced the same biological effects as the natural hormones. Thus we now have ample corroboration of the thesis that we have here servo-mechanisms which are conditioned by the structure of the molecule.

The particular cases of these two hormones are also of interest for the light which they throw on the specificity of resonance. The point here is that the molecules of oxytocine and vasopressine are amino-acid chains of great similarity. Putting the formulae of these two chemicals side by side—or, rather, the lists of amino-acids which form their chains—we have:

* We know what systematic use has since been made of artificial adrenalin (for though the effect is only transitory, the adrenalin being merely a signal, this substance is of great use in accidents, for it raises the blood-pressure of injured persons suffering from shock).

OXYTOCINE		*VASOPRESSINE*
cystine		cystine
I		I
tyrosine		tyrosine
I		I
isoleucine	*	phenylalanine
I		I
glutamine		glutamine
I		I
asparagine		asparagine
I		I
cystine		cystine
I		I
proline		proline
I		I
leucine		lysine
I		I
glycine		glycine.

In other words, in both cases we have nine amino-acids, the two chains differing only in the third and eighth links in them (marked with *). Though so slightly different one from another, these are two distinct substances, having very different effects.

* Perhaps this point will be still more clear if we glance at the points of difference. The simple formulae (i.e., those merely showing how many of each kind of atom is present) are, in the first point of difference:

Isoleucine: $C_6H_{13}NO_2$
Phenylalanine: $C_9H_{11}NO_2$, whereby the second substance is seen to contain three more carbon and two less hydrogen atoms, and, in the second point of difference:

Leucine: $C_6H_{13}NO_2$
Lysine: $C_6H_{14}NO_2$.

Here the second substance seems to differ from the former only in containing one more hydrogen atom. Yet it is not merely a difference of one hydrogen atom, but a matter of where the hydrogen atom is, indeed, how the substances are put together with regard to all their atoms. Without going into their three-dimensional structure, we find that when their formula is written to give merely a hint of their set-up, they are:

Leucine: $\begin{matrix}CH_3\\CH_3\end{matrix}\!\!>CH.CH_2CH(NH_2).COOH$
Lysine: $NH_2.(CH_2)_4.CH(NH_2).COOH$,
whereby it needs only a glance for the layman to realise that " more or less the same set " of atoms are here assembled in very distinct patterns.

The features of the resonance of the hormones change sharply with the aspect of the molecule. It is suggestive of the fascinating way in which a touch on the control of our radio set causes the receiver to cease to be " in tune " with Paris PTT and instead be " in tune " with Belgrade on the one side or the BBC's transmitter on the other. The only difference (from the " in tune " point of view) is that instead of being subject to the irrational distribution of wavelengths on the " medium wave " band, our organic substances themselves assumed their precise layout. Our problem is to work out the mathematical framework of each organic substance by which to recognise the " resonances " it is capable of and the servo-actions to which it can give rise when introduced into a given medium.

Beyond these examples, let us note that the analysis of the " big hormones " has already begun, and work on some of them has made progress. Quite recently we have had two sensational results. There is the analysis of the hormone designated as ACTH,* made by C. H. Li of the University of California, and the patient work which Professor Sanger brought to a close at Cambridge University in 1954, revealing the structure of insulin, the amazing hormone which controls the glycogenic function of the liver.

Let us here be quite clear what we mean: the " numerical " composition of this protein had long been known—that is to say, the old-fashioned formula which only told us how many atoms of each constituent element it totalled. That, however, was a Pyrrhic triumph indeed, because what gives an organic molecule its properties is *its architecture*, and the real problem is to discover that internal layout, *where in any molecule the various elements listed in the old-fashioned formula are placed, and how.* Sanger succeeded in doing this with ox insulin. He used a number of procedures, based on chromatography, continually breaking up thousands of millions of molecules and systematically examining all the characteristics of the fractures, thereby gradually building up a complete picture of how the molecule was constructed. In the end, it proved to consist of two parallel chains. One chain had twenty-one the other thirty amino-acids in it, the chains being

* By that hieroglyphism so dear to the specialist, these letters stand for four English words: " adreno-cortico-tropic-hormone ".

joined together by two bridges of sulphur atoms. By this brilliant work, Sanger brought the insulin molecule down to the same old amino-acids, which we find at the basis of all living matter. His work made it clearer than it had ever been before that the properties of the molecule are dependent on the manner in which the parts are put together. Now that the structure formula of insulin is known, it only remains to synthesise a molecule with the same structure, to see if it has the same properties. There is every reason to expect that it will have. (See Figs. 3 and 5.)

The important thing, then, is to understand that the hormone mechanisms derive from the common phenomenon dominating all living matter, namely that the presence in a suitable medium of certain primary substances prompts the formation from the medium of secondary substances capable of a specific chemical action, and in due course, by a more or less complex cycle, capable of acting on the primary substances themselves. This plan is basic. Behind all the terms previously suggested to describe the process—catalysis, ferment, hormone, enzyme, zymase, vitamin—there is to be found one and the same natural phenomenon, the control action which certain developed molecules exercise on their environment by sheer reason of their structure.

THE GENERAL SCHEME OF CONTROL MECHANISMS

It goes without saying that when the world of living things began, these highly evolved molecules which we have just been considering did not exist. The most one can admit is that a few molecules of, say, oxytocine or vasopressine might have appeared by pure chance. But even so, they would have been only isolated particles, outside any organised system. At such an early stage they would have lacked the substratum in which they might do useful work.

This, however, is not what we are after for the moment. Indeed, we will postpone consideration of this matter of the organisation of the environment to our next chapter. What we need to do now is to get to know the active forces which will have to play their part within such organisation.

The mere fact that our molecules are machine-tools of itself presents a problem which is astonishingly vast. For, the moment

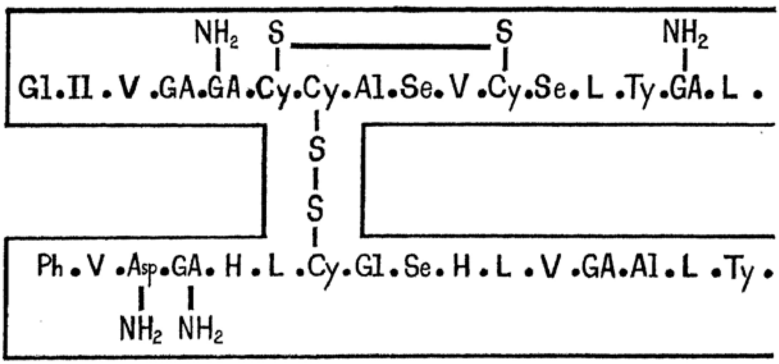


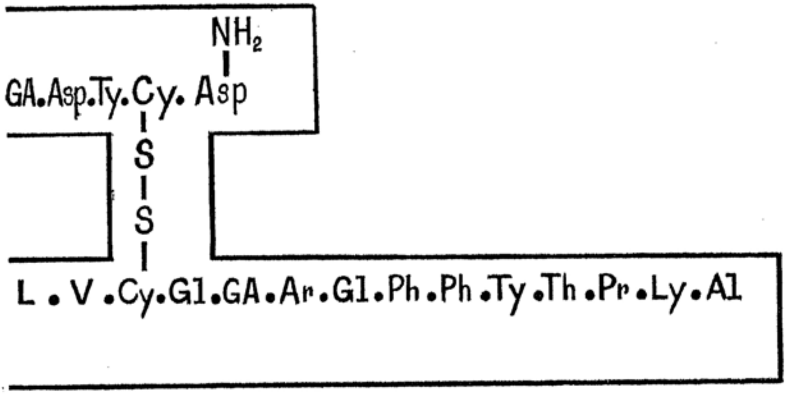
FIG. 5. THE INSULIN
How the constituent parts of an insulin

Key:

Gl	Glycine	$CO_2-CH_2-NH_3$
Al	Alanine	$CO_2-CH_3-CH-NH_3$
V	Valine	$CO_2-CH-NH_3-CH\left\langle\begin{matrix}CH_3\\CH_3\end{matrix}\right.$
L	Leucine	$CO_2-CH-NH_3-CH_2-CH\left\langle\begin{matrix}CH_3\\CH_3\end{matrix}\right.$
Il	Isoleucine	$CO_2-CH-NH_3-CH\left\langle\begin{matrix}CH_2-CH_3\\CH_3\end{matrix}\right.$
Se	Serine	$CO_2-CH-NH_3-CH_2OH$
Th	Threonine	$CO_2-CH-NH_3-CHOH-CH_3$
Ph	Phenylalanine	$CO_2-CH-NH_3-CH_2-C\left\langle\begin{matrix}CH = CH\\CH - CH\end{matrix}\right\rangle CH$

one speaks of the special nature of control-mechanisms, there is nothing against our generalising the theory suggested earlier on and imagining a vast schedule laying down the effects any molecule whatsoever will have in any environment whatsoever. Of course, in most cases nothing, or almost nothing, would happen. On the other hand, in certain relationships, given molecular form and form of substratum which fitted, we should see our molecules immediately cause a tremendous transformation of their medium.

Certain substances act on many others. Some substances, on the other hand, have very limited fields of action. However, (leaving the enzymes out of it), we know of certain very general specificities. For instance, there is the well-known instance of the



MOLECULAR SET-UP
molecule (each in itself complex) are arranged.

Ty	Tyrosine	$CO_2-CH-NH_3-CH_2=C\left\langle\begin{matrix}CH=CH\\CH=CH\end{matrix}\right\rangle C-OH$
Asp	Asparagine	$CO_2-CH-NH_3-CH_2=NH_2=CO$
GA	Glutamic Acid	$CO_2-CH-NH_3-CH_2-CH_2-CO_2H$
Ar	Arginine	$CO_2-CH-NH_3-CH_2-CH_2-CH_2-NH-C\left\langle\begin{matrix}NH_2\\NH\end{matrix}\right.$
Ly	Lysine	$CO_2-CH-NH_3-CH_2-CH_2-CH_2-CH_2-NH_2$
Pr	Proline	$\begin{matrix}CH_2-CH<CO_2\\ \vert \\CH_2-CH_2-NH\end{matrix}$
H	Histidine	$CO_2-CH-NH_3-CH_2=C\left\langle\begin{matrix}CH=NH\\ \vert\\N-CH\end{matrix}\right.$
Cy	Cystine	$\left.\begin{matrix}CO_2\\NH_3\end{matrix}\right\rangle CH-CH_2-S-S-CH_2-CH\left\langle\begin{matrix}CO_2\\NH_3\end{matrix}\right.$
$GA-NH_2$	Glutamine	$CO_2-CH-NH_3-CH_2-CH_2-CO-NH_2$

lipases, which hydrolyse (i.e., dissociate the molecules of) fats and a wide range of esters and alcohols. On the other hand, we can point to other cases, where the substance limits its action on its substratum to one particular specific action. It is also common ground that in the different types of living organism the same function may be affected by substances which are of slightly different physiognomy. This need not astonish us, for we have already observed the unbelievable variety of the possible chains formed from the amino-acids, and we should realise here that secondary functions may be added to one and the same basic property. The case of insulin is typical. Sanger has shown that there are slight differences of composition between the insulins

obtained from the pig, the ox and the sheep, while a plant has been identified in the Bermudas which furnishes a substance which, though it has a very simple structure-formula, apparently has the glycaemic effect of insulin. In other words, it would seem that for each particular control we may presuppose a fundamental functional group.

In our view, the great task of chemistry in the years to come will be to elucidate the vast general schedule which will be the multiplication table of all these control mechanisms. I do not suggest we can ever actually map it out completely on paper. That would be far too vast a task. But at least we should be able to outline reliable classifications, in other words, codify a very general "language of structures and their roles", a sort of summary of a general schedule. When this task has been realised, chemists will be able to set no matter what question and get a reply, giving them a notion to what "cycles" any substratum is likely to give rise. This would give very valuable indications regarding the cycles of activity of living matter.

When we think of such a table, there is one "class" which immediately draws our attention. It is that (supposing of course it does exist) of the molecules which, when placed in a given substratum, control it by constructing from it facsimiles of themselves, which would mean that when present in the appropriate medium they would be self-reproductive. In the algebra of control-mechanisms they would play the part of identical transformation in the theory of groups, or, if a simpler comparison is preferred, they would be like that function which in ordinary algebra is its own differential coefficient.

However, we must be clear about one thing—and this is a concept on which one cannot insist too much: this state of self-reproduction demands both a precise molecule and a precise appropriate substratum. It would be nonsense to speak in completely general terms merely of such a thing as "a self-reproducing molecule". No molecule could produce anything without the necessary raw materials.

Here the reader may jump to the conclusion that the molecule of biology which possesses this self-reproductive constituent will be found in the gene. I assume, of course, that he is already well aware that the cells which ensure the reproduction of a living

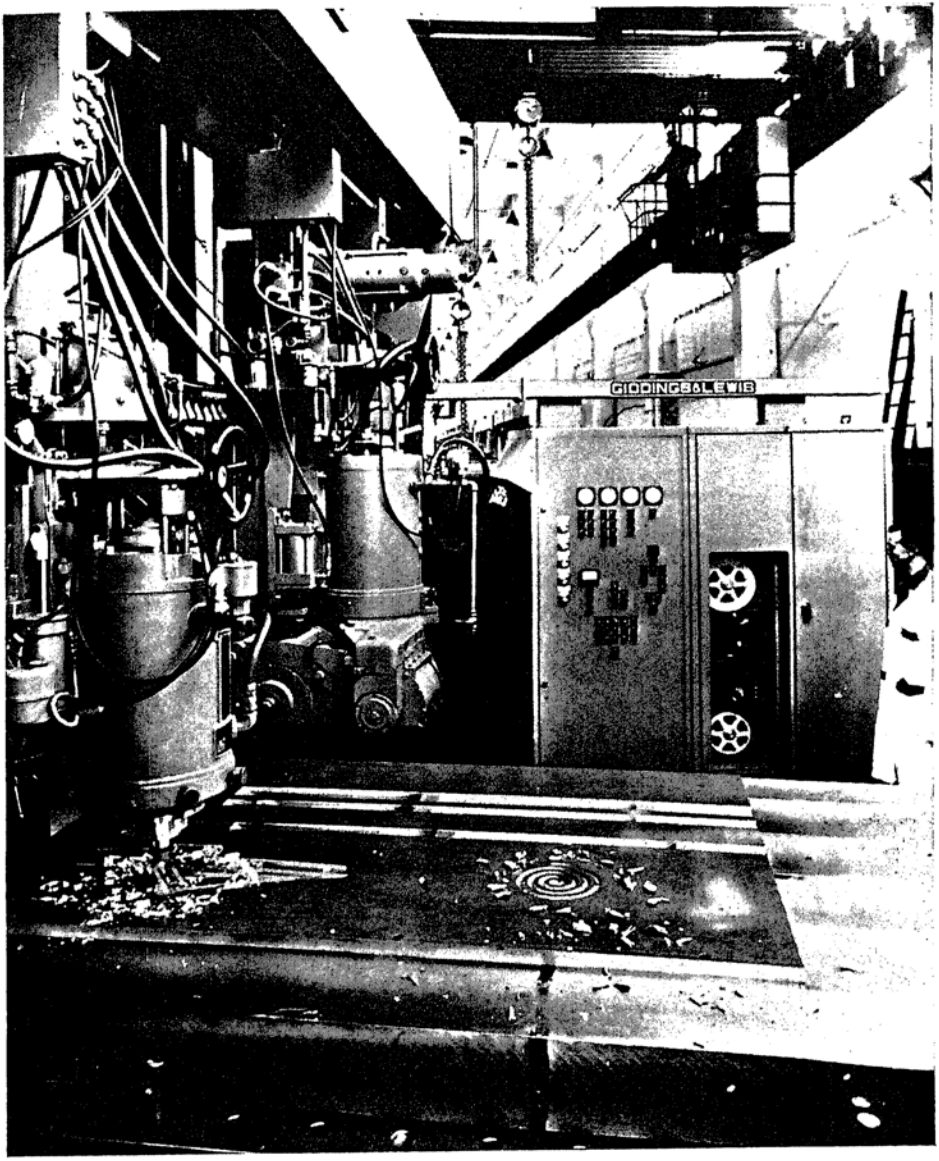


PLATE I

A modern electronically-controlled machine-tool. In one operation complex cuts, including a spiral, are made in a sheet of aluminium, all adjustments and movements of the tools being automatically controlled by the servo-mechanism seen in right background. The spools handling the magnetised " programme " ribbon can be seen.

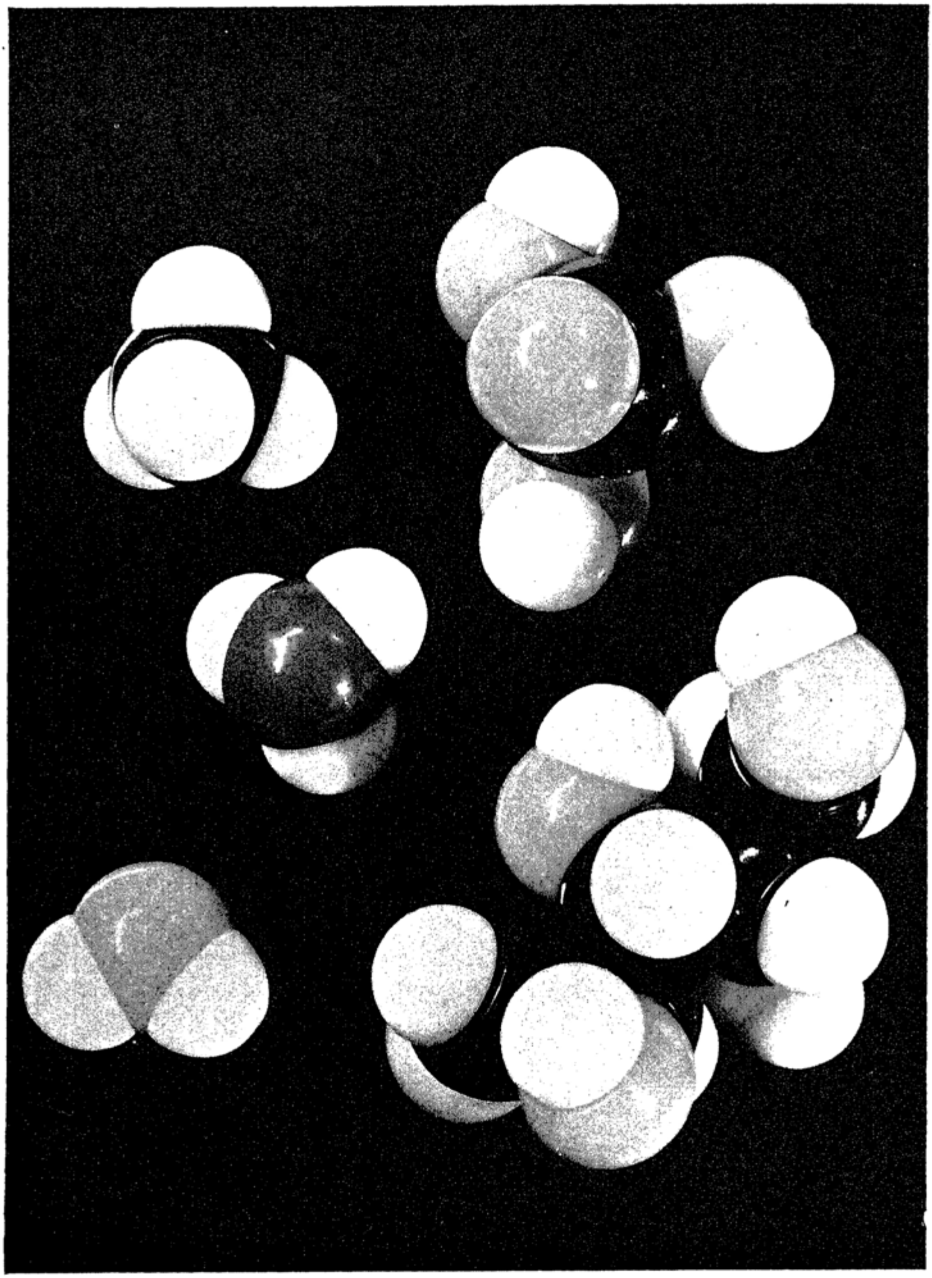


PLATE II

Basic molecules, represented by balls of different sizes and colours. *Bottom left*—water, *centre left*—ammonia, *top left*—methane, *top right*—orthophosphoric acid, *bottom right*—deoxyribose, a nucleoside which enters into the composition of deoxyribonucleic acid. (*The models for this photograph were kindly supplied by Messrs. Catalin Ltd.*)

creature, from the humblest protiston to *homo sapiens*, contain a certain number of so-called " chromosomes ", these being collections of units known as genes which are the real repositories of heredity, reproduction taking place the moment a series of genes give birth to a like series. As a matter of fact, the chemical nature of the specific self-reproducing particle is now known to us. It is a long molecule called deoxyribonucleic acid!

Quite apart from this gene concept, however, we had every right to make the very general suggestion that there was a certain principle of self-reproducing matter, for the various units known to biochemistry which possess this property of self-reproduction have remarkably similar chemical properties, no matter whether they are viruses, nuclear genes or cytoplasms. In every case we come upon the same substance: the nucleic acid to which reference has been made. Everything proceeds, in fact, as if in our scheme of servo-controls it was this acid which bore the blue-print of identical transformation which we seek.

We find the starting-point of every living creature is always a nucleoprotein formed by the association of deoxyribonucleic acid and a protein. The nucleic acid is the self-reproducer, while—how, we shall see later—on one and the same foundation structure it is able to assume a fantastic number of different forms. Hence its ability to join up with the very varied proteins which constitute the " scheme " of so many different living creatures. The proteins perform specific acts of servo-control which determine the physical organisation of the creature.

Thus, beyond the details to which we too often pay attention, one can discern the remarkable unity of living creatures. All alike essentially start life from nucleoproteins, and all that follows in their being is the fruit of reactions dictated by the nucleoproteins.

These questions, of course, will be more fully examined later. Here, however, we may allow ourselves one important observation: to repeat, *a priori* the property of self-reproduction only applies when the nucleoprotein finds itself in an environment of the right composition. If that composition, or its physical conditions, are changed, the servo-mechanism ceases to offer this picture of perfect similarity. This means that slight modification of the environmental medium results in the production of a particle which is not identical, but slightly different. This for us

is a most valuable indication. It gives us an idea of what effect variations in the environment may have.

For the moment, however, let us refrain from setting out on the marvellous road these notions suggest to us.

JORDAN'S FORCES

To complete this survey of molecules as machines, it may be profitable to glance back at the study which during the past fifteen years modern chemistry has made of the problem of the servo-mechanisms exercised in the molecular world.

First, there is the most exciting study of the way in which our machine-molecules act. What exactly is the process of control mechanism like? We have ventured two comparisons, one with machine-tools, which as it were stamp the particles they process, the other with a tuning-fork which at a distance brings the environmental medium into tune. Which comparison holds? Perhaps both processes are involved.

The first point of view is that of classical physics. It has been developed very lavishly, particularly by Pauling and Delbruck. These two physicists have endeavoured to work out the principles of a sort of molecular mechanics, as if enzymes worked on their substratum like sewing-machines on cloth.

Beyond these questions of actual manipulation, we have the work of Born. Born has applied quantum mechanics to the study of catalysis. His work has shown the reality of action at a distance, and this has served greatly to broaden our outlook, for if we once allow that the primary molecule need not be in direct contact with its substratum to exercise control on it, its power can be considerable.

These are the directions in which a number of physicists have directed their research, leading to results which are still disputed, or at least, are the subject of heated debate. But it is interesting to glance at their essence, even if merely to get some notion of what current servo-mechanism chemistry looks like.

First of all, we have alluded above to the self-reproducing molecule. The operation of such a molecule may seem puzzling. From the pure point of view of chemistry, however, can a structure of molecules introduced to a given medium make a structure like itself out of the atoms in that medium?

To this fundamental query several answers have been advanced. That of Friedrich Freska takes first place. Freska attempts to explain the servo-mechanism process purely by the electrostatic forces of the particles of the gene. That is to say, he seeks the way out in a simple physical action of classical form. According to this, we should see an organic molecule as a series of little dipoles, that is, of couples formed by the association of a positive and a negative electric charge, the charges being supplied by the constituent atoms, and occupying given positions. These charges then create a field capable of acting on the atoms in their vicinity in such way as to communicate to give them a precise orientation. One may suggest the parallel of a collection of small magnets which, when disposed in a certain pattern, might well produce a complex electro-magnetic field which, working at a distance, would play havoc with ships' compasses.

But such an explanation hardly holds, and Pascual Jordan has submitted it to systematic refutation. What Jordan points out is that, if the orientation of the atoms were merely due to such electro-magnetic forces, any electric field ought to act on any molecule. Then, all this specificity of biological action with the gene attracting only molecules of a precise form would vanish. Besides, decisive experiments were made during the second world war by Schramm and Müller, showing that even when one treats the free amino groups of the tobacco mosaic virus with acetylene, this does not make the slightest difference to the process of reproduction of the virus. This completely overthrows the electricity scheme.

What Jordan suggests is a totally new theory, based on the idea that a molecule apt to multiply may be prone to be broken up into a certain number of parts which possess the property of exercising attraction on other particles (like or complementary) in the environmental medium. If this is so, when we imagine a definite macromolecule introduced into a medium, with the various elements necessary to form it present in the free state, they will be automatically attracted, like to like. They will then take up positions parallel to the various parts of the macromolecule, after which these unit parts may link together. Thereby a facsimile macromolecule is born. Using the language of biocybernetics, we should put it like this: whereas the necessary spontaneous union of the constituent parts of such a macromolecule in the desired disposition would of

itself be most unlikely under the effect of these specific forces of attraction, by Jordan's theory the probability of the phenomenon is very greatly increased when a model molecule is introduced close at hand in the environmental medium.

To explain this, Jordan presupposes a force of resonance, independent of any of the classical kinds of force. Earlier physics, as we know, made an attempt to reduce all the forces of the universe to two types only, gravity and electricity. It was the ambitious objective of a " unitary theory " to effect a synthesis of the two. But modern physics cut that much too seductive edifice to pieces. For instance, as early as 1927 the Chinese physicist Wang showed that the quantum theory implied the existence of special forces dependent on the attraction of one molecule for another (so-called Van der Waals forces), and in 1935 the same physicist was again to fall back upon quantum interaction to explain the very special forces which act inside the atomic nucleus (nuclear forces).

Finally, Jordan invoked the same principles of quantum mechanics again in 1944, to show by a simple calculation that a force of attraction of the nature suggested by Wang did exist between one molecular structure and another. Jordan was now also able to point to the work of Eucken's team regarding the rotatory movements of the radicals in organic molecules. This research indicated a force of attraction which varied as the cube of the distance. Jordan's theory was beginning to undergo substantial development. Most notably, it had apparently for the first time offered an explanation of the formation of antibodies which, it is common knowledge, may appear in the blood serum in such quantities that the number of molecules formed is eventually millions of times greater than the number of the antigene molecules.

Jordan's theory was to be taken up in France by Fernand Pasquier, who in 1947, in a first communication to the French Academy of Sciences on the matter, finally lent it his support. Pasquier had set himself to making Jordan's theory more exact by developing calculations which took account of the natural identity of the particles concerned. This seems to dispose of the objection which Pauling and Delbruck had made. For these two physicists were prepared to admit the validity of Jordan's calculation, but insisted that this force of quantum resonance

must also exist between two particles of different structure. Pasquier definitely proved that the force of attraction is not the same when different molecules are involved. From Pasquier's work, moreover, another point of great interest to biologists emerges. When one examines Pasquier's formulae, one is struck by the fact that the difference in the interaction is greater in proportion as it concerns particles which have reached a higher degree of organisation.

Jordan's great contribution has been his drawing attention to the fact that recourse to the equations of modern quantum mechanics unquestionably indicates the existence of action of a very special kind which is not to be neglected in our study of the molecular servo-forces.

THE WINTER EFFECT

The end of the fascinating story of the new insight into the nature of life is given us by modern physics. Still more astonishing ideas, which extend those we have just examined, have been put forward by Jacques Winter in the past decade. This French physicist, the growth of whose fascinating theories one follows year by year, introduces a new factor in the life process. This is—the water which serves as the ultimate medium of all these phenomena.

For this we must not forget: it is in a watery medium that life was born and it is in a watery medium that it has always existed. The larger part of our own bodies is water. When in biochemistry we speak of the action of particles of matter on each other at a distance, it should be understood that we invariably presuppose the action taking place through the intermediary of the cellular water of the organism. Does not the existence of such a medium throw a special light on all these phenomena of interaction? Especially as the resonance effect is greatly increased in the watery medium?

This is precisely what has interested Winter. He turned to this question, as vast as it is ungrateful, in view of the paucity of previous work by modern physics on the structure of liquids. What is this? Am I suggesting that the hydrodynamics of our schools is faulty science? Not in the least. What there is of it is satisfactory. But, quite apart from the field of biology, there are

still quite a considerable number of phenomena which hydrodynamics has failed to explain. I need mention only the peculiar property by which, when subjected to high pressure at 0°, water becomes not more, but *less* viscous. The truth is, the study of liquids presents a remarkable gap in our knowledge. The only large-scale profound modern studies are those of van der Waerden and Frankel.

Let us turn our attention for a moment to the state of a substance immediately after its solution, that is to say, when the energy communicated to its atoms has proved just sufficient to break down the crystalline organisation which they possessed in the solid form. Is it not reasonable to suppose that the destruction of the crystalline network is achieved by the detaching of more or less important blocks of it, just as when thaw sets in the first phase is the break-up of the continuous ice surface of a lake or a river into large floes?

This is what van der Waerden suggested in a memorable paper published in 1941. He explained that when water is at a comparatively low temperature its molecules are not absolutely free. They are grouped in clusters. He further showed that such clusters of molecules can be stable. If we now recall the shape of the water molecule—a circumflex accent, the oxygen atom at the peak, the two hydrogen atoms at an angle of about 105° * on either side—we can surely discern some interaction taking place between the hydrogen atoms of the various molecules. Thus van der Waerden showed that in water in this state we have to presuppose the existence of " floes " of order, separated by channels of really fluid disorder.† Quantum mechanics was immediately applied to the study of the functions of such molecular clusters.

Now, when a macromolecule is introduced into water, an immediate result is that it upsets the distribution of the clusters of water molecules, by its proximity imposing on them a precise structure. In other words, it controls their organisation. This leads to the admission that the macromolecule may well be the starting-point for a " chain of clusters ", further, that if nearby

* Ephraim describes these " floes " as " ice-type " polymerised molecules, consisting of a number of H_2O molecules linked together. Water is far more fanciful a substance than we usually realise. Even in its solid form it remains rich, for in addition to ordinary " lighter-than-water " ice, five other kinds of ice, all heavier than water, have been recognised.

† See footnote to p. 83.

there is another macromolecule, also causing a chain of clusters, these two chains may resonate, whence an attraction which differs from Jordan's force.

In other words, should we not bank on the existence of a new force, one capable of explaining more than one biological phenomenon? For instance, we may assume Winter's force to exist in the attractions between genes. With this thesis to support us, we next may turn our attention to the striking fact that even when the ribbon which bears the genes is looped or knotted, a male cell invariably couples on to the corresponding gene of a female cell. Likewise, we should have an explanation of that movement of bacteriophages towards microbes which seems to be suggested by a number of recent electronic microscope photographs, or of those notorious experiments in which Rothen established the existence of specific attraction between antibodies and antigens, even through membranes several hundredths of a millimetre thick, at distances where the ordinary molecular forces of attraction are non-existent.

The principal interest of the Winter effect, however, has been to furnish a very generalised explanation of the action of those astonishing machine-tools of the living factory, the enzymes. It must be understood that chains of resonance form between enzymes and certain secondary molecules with a given structure. The way in which a very feeble concentration of enzymes results in great output is to be explained by the fact that the presence of the enzyme may at once give rise to numerous clusters of molecules. Indeed, experiment confirms that when one increases the concentration of the enzyme above a certain value this does nothing to increase the reaction. The reason for this simply is that when the remaining chains of clusters no longer have a structure apt to assure the link-up, new chains cannot be set up.

Winter's force possesses a considerable radius of action. Whereas the electro-magnetic forces of classical type die out at a comparatively small distance, Winter's force imposes itself at distances of several microns, even several millimetres. How fascinating this is as explanation of biological mechanisms may be imagined.

On the other hand, the speed of propagation is very slow. The action does not start up at all till several seconds have passed. But this, after all, fits in very well with the general slowness of

biological transformations. Besides, we have to bear in mind that there is in all this rigorous specialisation. Winter's force links together not just any molecules, but only those with an appropriate structure. This is a natural result of the resonance principle outlined above. It is equally important as explanation of the very selective character of all biological reactions, for electric fields act indiscriminately on all charged particles.

Finally, we must observe that Winter's force appears to be extremely sensitive to the conditions of the medium. In particular, it varies considerably with temperature. This is of course because warmth has a powerful effect on the structure of the molecule clusters. This is an important fact when we recall that life often permits only very slight departure from very narrow temperature ranges. Our classical chemistry, on the other hand, within very wide limits admits continuous variation of the speed of reactions in proportion to heat. It is further understood that any other factor which affects these clusters of molecules affects the biochemical forces in the same way. This is the case with the acidity of the medium, the concentration of molecules, even the presence of impurities. All of this also agrees with the findings of biology.

Winter's theory has been given interesting detailed elaboration by the work of Mme Andrée Goudot. In two communications published in 1951, this research worker showed how the molecule clusters might play a part in the reproduction of genes. Transmitting from a distance the influence of the various parts of a molecule, clusters build up one on another till the association of atoms to form a facsimile molecule is ultimately provoked. Mme Goudot also indicates a possible way of understanding how negative catalysts act and has worked on the way in which links between enzymes and proteins are established.

We may also here record a contribution to the problem by M. Destouches, who has written an interesting study on the process of autosynthesis which brings about the functions of clusters. This French worker seems to give some support to both Jordan's and Winter's theories.

Does this then mean that, after all I have said above, Jordan and Winter really agree? No, we are still far short of that. One should not forget how great the abyss was which only yesterday still separated physicists from biologists. Only a small number

of the latter knew how to handle the equations of wave mechanics. Nor can we assert that the theories of either Jordan or Winter are perfect in their present state. Both are very recently conceived theories, both are insufficiently supported by systematic analyses. But though they play no direct part in my argument and are not mentioned from now on in this book, I nevertheless felt it wrong not to outline what they have suggested. It has been the purpose of this chapter to provide the reader with *all* the ideas which have been tabled about this amazing chemistry of servo-mechanisms. It is, however, only the fact that this chemistry exists that is essential here. Some of the ways in which these servo-mechanisms work are known. Others are still under debate. But what does matter to us is that side by side with the old-style chemistry there is now this new chemistry of servo-mechanisms. That they exist is a fact, and it is the part these play in the processes of life that we can now proceed to examine.

CHAPTER V

Cybernetics and Biocybernetics

BEYOND THE FRONTIERS OF CLASSICAL PHYSICS

WITH the appearance on Earth of amino-acids capable of getting themselves attached one to another, we have reached the core of the problem. The chains these amino-units thus form prove to be machines which affect the probability of events in their environment. Starting from here, let us now try to see how it was that evolution led inevitably to the birth of " living " matter.

We started with the assumption of chance reactions, a development which was not directed. There were amino-acids, but *a priori* we suppose them to join together and separate by chance. One might expect them to produce an enormous number of different combinations.

At least, this would be the position, if it were only chance that played a hand. The amino-acids do not form innumerable haphazard combinations. The existence of control mechanisms modifies chance. It lends phenomena a direction, a definite direction. Ineluctably, this means that *the usual laws of physics cease to be valid.*

This is the suggestion I made in the introduction to this book. Till yesterday, physics was a science dominated by pure chance. Its principles were based on recognition of the autonomy of all phenomena in the universe, including that of all the atoms which enter into the composition of any substance.

But, when all is said and done, that was only a theoretical view. On our earth all the phenomena we know are in fact linked one to another. It would be difficult to point to any two events of which one could say that there was not at least a thousand-millionth part of a chance of causality between them. After all, we see the

same thing on a universal scale. The mathematician does not find that totally Gaussian random distribution of cosmic radiation which pure chance would presuppose. True, in the physics of yesterday such coefficients of interaction were quite negligible. That is why science was able to erect the wonderful theoretical edifice with which we are familiar. For instance, as far as its powers of observation went, physics was able to presuppose pure chance governing the molecules of a gas flowing in all directions. The same goes for many other independent entities to which the laws of large numbers apply. Thus was elaborated the theory of kinetics on which modern thermodynamics and most notably Carnot's famous theorems have all been built. Thus too was postulated the famous concept of entropy, namely the measure of disorder, which, as I recalled in the introduction, in principle cannot but increase as time goes on.

Now, if in real instances chance is not absolute, all these considerations have to be revised. After all, our earlier reflections called for some correction of this notion of absolute chance. But so far only modest correction was required. Here we must take cognizance of the fact that the existence of these molecular servo-mechanisms upsets chance to a very considerable extent. It is therefore rather surprising that more than one eminent physicist should have been so disconcerted when he found that some of the standard laws of physics seemed not to apply at all to living processes. It had simply not occurred to them to notice that the world of biology is essentially one of such servo-mechanisms, factors which were left out altogether by standard physics when it worked out its laws.

I myself find it impossible to adopt the point of view which would see in living beings entities apt on occasion to be outside the laws of physics. The truth of course is that the standard physics of yesterday only dealt with a special realm of things. Cybernetics, on the other hand, does undertake a general study—of all systems in which servo-mechanisms assume all possible values. In the new architecture, classical physics is reduced to the description of a special case—the special case in which servo-mechanism is reduced to 0. Thus cybernetics is to standard physics what in celestial mechanics relativity was to Newton's law. This does not turn out to be "wrong". It is merely a special case.

It is instructive here to glance at the way the standard laws of physics are changed when servo-mechanisms come into play. Let us start with that famous law of action and reaction which was till yesterday inscribed in the first pages of all the textbooks. Standard physics tells us that when we place a pound weight on the table, the table opposes an equal force in the opposite direction. That indeed is very true, because between these two systems (the weight and the table) there is symmetry, or balance. But the moment the disproportion characteristic of servo-mechanisms is introduced, the question looks very different. Then, theoretically, a force as small as one wishes can control as heavy a weight as one wishes. It can over-balance its natural inertia.

There is no limit to the extension of the field which a servo-mechanism can cover. Take only the everyday case of a speaker before a broadcasting microphone. His voice sets up minute vibrations in this. Immediately, millions of loud-speakers come into operation. Their power comes from the electricity mains or a battery, but it is all controlled by that one vibrating membrane. There we have the sort of " organising force " which classical physics utterly failed to examine.

Among the basic laws of standard physics we may also recall that of the conservation of momentum and kinetic energy when two bodies collide. When it comes to the play of servo-mechanisms such considerations cease to be applicable. If the tap of the billiard ball releases a servo-mechanism, so trifling a blow can set a considerable mass in motion. When this happens the laws of impact are all set to naught.

True, the principle of the conservation of the total energy is not changed. It remains superior to all these laws. But the point is that the existence of a reservoir of energy liable to be thus brought into action at a given moment (the basic principle of a servo-mechanism) may throw a completely new light on real events in the world. It manifests itself in laws quite as rigorous as those of standard physics, laws governing the characteristics of servo-mechanisms, and the greater the power of servo-mechanism the more these new laws depart from those of standard physics. Imagine pseudo-billiard balls whose movements are controlled by servo-mechanisms. There is nothing against arranging that when the balls cannon off the edge of the board,

the angle of reflection is different from the angle of incidence. One could similarly arrange for the results of impact between two balls to be most unexpected.

It is considerations like this that we need to bear in mind if we would grasp the tremendous interest of cybernetics. The word large enough to indicate the scope of this science does not exist. We can without hesitation say that cybernetics is the key achievement of the twentieth century. No other discovery of technology can be compared with it. It is of enormous importance in its practical applications—automation and electronic computing. But it is of greater value still in the realm of theory. For what it offers us is a new, generalised physics, a physics capable of embracing not merely standard physics but also the physics of life, the realm of a power of servo-control which from very minute potentials indeed has of itself expanded into a power which is tremendous. It is deplorable that so far very few scientists have grasped the real meaning of cybernetics. There have been far too many works which restrict consideration of it to a few paragraphs of minor importance. This is particularly outrageous when in fact it is really a superior form of physics.

It is, I repeat, the great event of our age, and in the framework of this tremendous event I feel that we must create a new term, biocybernetics, to designate a new chemistry of servo-mechanisms, a chemistry which is to standard chemistry what cybernetics is to standard physics. The word biocybernetics is chosen to make it quite clear that because its proper realm is that of bio-chemistry, this new chemistry of servo-mechanisms must take account of the general laws of cybernetics concerning retroaction, loop-circuits, and networks of feed-back. For, let us not forget, these chemical servo-mechanisms which we have examined appeared naturally, with the synthesis of rather complex molecules. Thereby events were stamped with that firm sense of direction from which emerged life itself.

THE FIRST STAGE: SELECTION

Since our chains of amino-acids are intrinsically imbued with a slight servo-mechanistic power, being capable of favouring the appearance of certain other chains (or, on the contrary, of destroying certain existing chains), we find ourselves on the road before us

faced with a chance which, by reason of the synthesis of certain chains becoming more frequent, is now slightly diminished. A process has started in which the dice of chemical chance are all weighted. To use the language of probability, the odds are no longer even. When we take the factor of time into account, we find we have a systematic one-way transformation working, by a procedure which the casinos of the world grasped very well when they opened roulette rooms in which the distribution of chance is slightly weighted in their favour. We all know the consequences. Whereas with odds even the banker and the players would all equally be losers and winners, the divergence of 1 in 37 which the rules of roulette lay down means that even if the gamblers were to go on indefinitely the banker would always win and they would always lose.

Examining the molecules which had appeared on this earth in its primitive stage, we therefore need to grasp that it is precisely those which are apt to take part in " cycles " which are favoured. For it is cycles of amino-acids that in fact come into being when the existence of one precise chain of amino-acids tends to favour the synthesis of another chain, which in turn gives rise to a third and so on, till we get a chain which will favour the synthesis of the first. Obviously, the substances produced in such cycles become more and more abundant. This is the initial stage of a development which implies selection. Natural developments lead to the preferential appearance of certain substances. The total of these increases with time, on the principle by which the accumulation of compound interest is self-accumulatory.

To take a comparison, imagine a lottery with a very large number of tickets. Lot-drawing then represents the appearance by chance of long molecules constituting a number of amino-acids. Were we to stick to standard chemistry, and presume every substance in our lottery to be independent of all the others, obviously, however long one went on drawing tickets, nothing would arise but the appearance of a series of numbers obeying the laws of chance, any number in the long run reappearing as frequently as any other.

But now let us suppose that whenever a number comes up which ends in a 0, that event for a certain time increases the likelihood of a number ending in 5 turning up. Suppose also

that the appearance of a number ending in 5 also increased the likelihood of a number which ended in 0 or 1. That conditioning of the lottery would change everything. For a time, things would proceed exactly as in a standard lottery, but once chance had provoked the appearance of a certain number of tickets ending in 0, we should have more ending in 5, and that again would favour the appearance of more tickets ending in 0 or 1, and so on. The process would tend to build up, so that in time, after a mere jumble of numbers, there would on the screen be an imposing collection of numbers ending in 0, 1 and 5. It was just the same in the great chemical lottery provided by the fluid medium of the primitive earth, energised by short-wave radiation. (Except indeed that here one has to take account of much more complex arithmetical rules.) The machinery of selection here worked so that in time the infinity of theoretically possible substances was dominated by compounds able to take part in cycles of servo-mechanism. By this process, in the end it was the compounds the more promising for life, that is to say, those with a certain power of servo-control, which came to be predominantly synthesised.

This is the logical consequence of a state of " dependence " between one and another of the various substances which are formed. On the one hand, in course of time, certain of them must appear in ever more preponderant numbers. On the other hand we also have the appearance of " cycles " of substances. This second feature of the situation implies the existence of a series of servo-mechanisms which favour each other. They are like so many closed circuits, the existence of which, as we noted in the preceding chapter, might theoretically have been presumed in the basic framework of our chemistry.

Let us note that the moment it reaches a certain stage of development, such a cycle logically involves the notion of " restitution ". Once we assume a primary substance (an initial chain of amino-acids) whose existence favours the appearance of a secondary substance, which in turn prompts a third, and so on till there appears a substance in the cycle which favours the birth of the primary substance, we are able to consider the primary substance and the remainder of the cycle separately, seeing in the cycle a mechanism which assures the reproduction of that primary

substance. We can even define a "factor of multiplication", which, under given conditions, is the measure of the number of molecules involved. We shall soon have an opportunity of examining this idea in closer detail.

A cycle may have any length whatever. But in practice, once we plunge into this labyrinth of servo-mechanisms, it becomes clear that it would be self-delusion to think we can merely consider what happens to the matter integrated into any single cycle. Far from this, the diversity of the feasible reactions rather invites us to consider that any matter may participate in several cycles, these possibly being further elaborated by side ramifications or complicated by chemical reactions into which the products formed also enter. Or one cycle may even be combined with another, the two cycles interchanging elements, merging their fortunes.

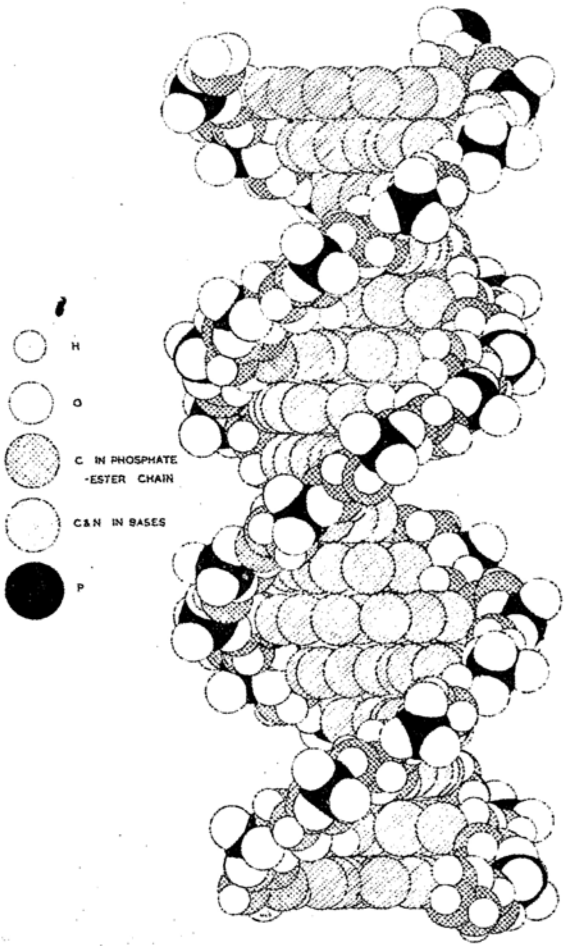
In this whirlpool we find the process of development by which a substance is created the destruction of which will allow the formation of another substance which will re-create the first. Yes, here, with the appearance of this state of palpitation and the perpetual building up and breaking down of matter, which is to become the prerogative of every living cell, we certainly are at the dawn of life. The picture which forces itself on us is that of a series of interlocking loops which by an endless process of transformation and organisation control all living matter.

THE SECOND PHASE: LOCALISATION

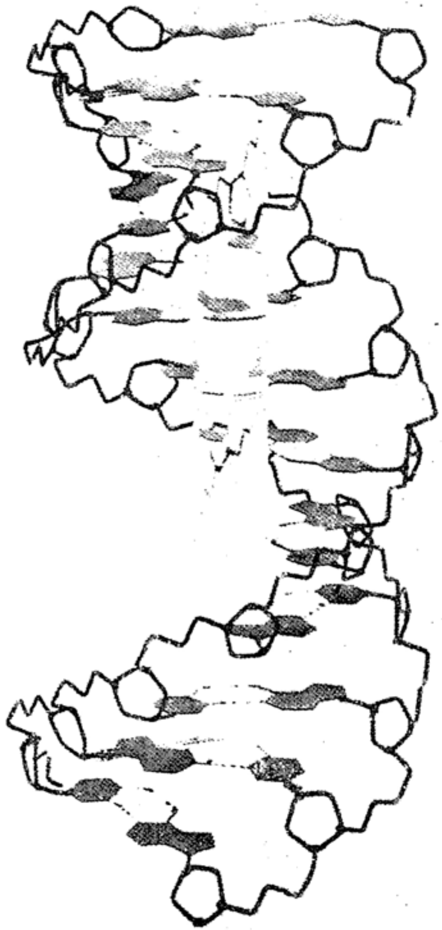
This network of interlocking loops continues, changing shape. Ever more rapid, ever shorter cycles arise, cycles which grow by themselves, absorbing ever greater quantities of the raw material. On the one hand they grow shorter in space, each particle tending to act in its own neighbourhood the moment it finds its medium, and on the other they grow shorter in time, therefore in the number of operations, since it is the more rapid servo-mechanisms which come to dominate the field.

Nevertheless, it is doubtful if this process could ever have culminated in giving birth to "living entities" without the "addition" to this phenomenon of the possibility of localisation. Now, we have already noted that, apart from this great cyclic play of servo-mechanisms effected by the amino-acids, there was one

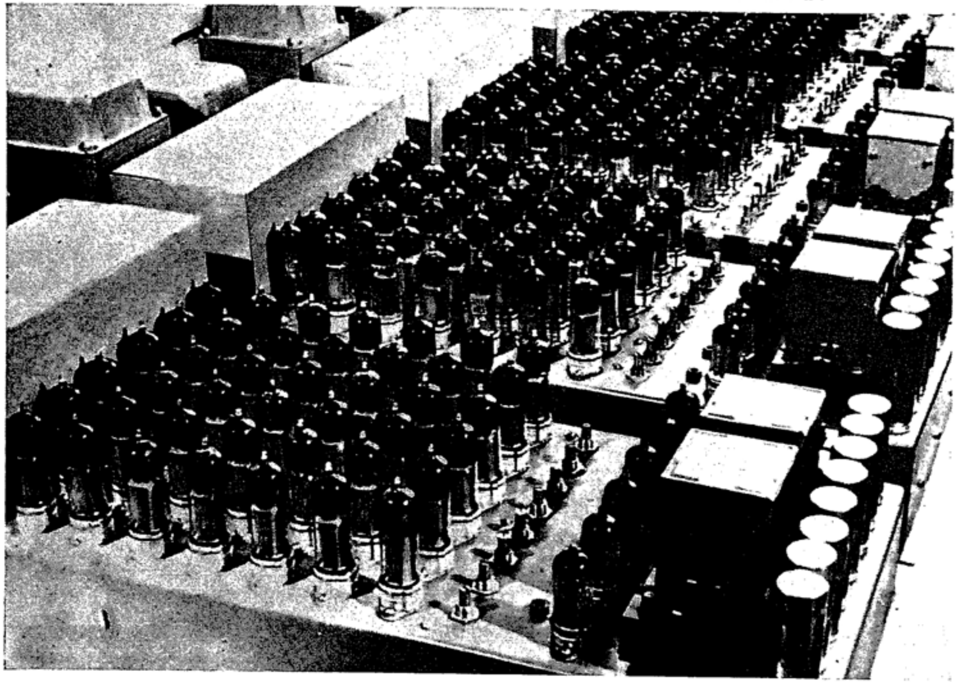
PLATE III. TWO REPRESENTATIONS OF THE DNA DOUBLE-CHAIN MOLECULE STRUCTURE



Left: Molecular model by Dr. M. H. F. Wilkins of King's College, London. (Either of the two parallel chains seems to be able to grow the other half.) *See page* 150.



Right: Diagrammatic representation by Dr. F. H. C. Crick of Cambridge University Department of Physics. (The cross-rungs referred to in the text can be seen as constructions of shaded and blank hexagons joining a pentagonal outline (a pentose sugar) of one half to the corresponding pentose of the other half.)



Left: (i)

COMPUTER BRAIN. Ranks of thermionic valves in a computing machine.

Right: (ii) DISINTEGRATION AND RE-MAKING OF A LIVING VIRUS

Above: An intact Tobacco Mosaic virus, 300 microns long (a micron is one ten-thousandth of a millimetre).

Centre: Dissolving the protein part away from the nucleic inner strand.

Bottom: The protein helix, which forms the wall of the particle, stood up on end.

These photographs were kindly supplied by Dr. H. Fraenkel-Conrat, of the University of California, who recently succeeded in thus taking apart a living virus and then putting the two parts together again to re-form the living entity depicted in the upper photograph. (See p. 129.)

substance which had the property *of direct self-reproduction.* This is deoxyribonucleic acid, an astonishing feature of which is its very simple chemical structure. This tends to corroborate the thesis which I ventured in my introduction: that though there was no probability that we should see any order appear of itself so long as we looked only at complex aggregates of atoms, the matter stood quite differently in the scale of simple associations. Now that is precisely what we have in deoxyribonucleic acid, whose foundation structure is a chain of *a priori* indeterminate length. It consists of an alternation of sugar and phosphate, the sugar in question, a pentose, providing the linking points. This chain may have been limited to only a few links at the dawn of life. The appearance of such a chain had a probability which was not nil, which meant that given the factor of unlimited time its appearance might be regarded as virtually a certainty.

This acid, deoxyribonucleic (in common chemists' parlance DNA), introduces order. It becomes the starting-point of ever greater order, leading at last to the formation of molecular mechanisms of ever better organisation, capable themselves of creating more order. The association of proteins with DNA indeed eventually gives rise to *a self-reproductory centre.* Moreover, this sort of association was bound to be possible, because the length of a link of the sugar-phosphate-sugar-phosphate chain is exactly equal to that of an amino-acid (3·5 angstroms). This truly extraordinary coincidence incidentally enables us to discover the basic mechanism of life. For by itself DNA could not create anything but a chain of identical deoxyribonucleic acid molecules. That would get us nowhere. On the other hand, by itself a protein has servo-mechanism capabilities, but appears to be incapable of realising its own immediate reproduction at a given point. Thanks, however, to the amazing identity of the lengths of their respective constituent parts, DNA offers the amino-acids a series of hooks of the right spacing for it to pick them up, to give birth to a given protein. (See Fig. 6.) This gives us a system which, on the one hand, thanks to the protein, is able to effect an organising action, and on the other, by reason of the DNA, is able to produce a self-identical system, that is to say, one which undertakes the same function on its own. From this moment, order cannot but increase.

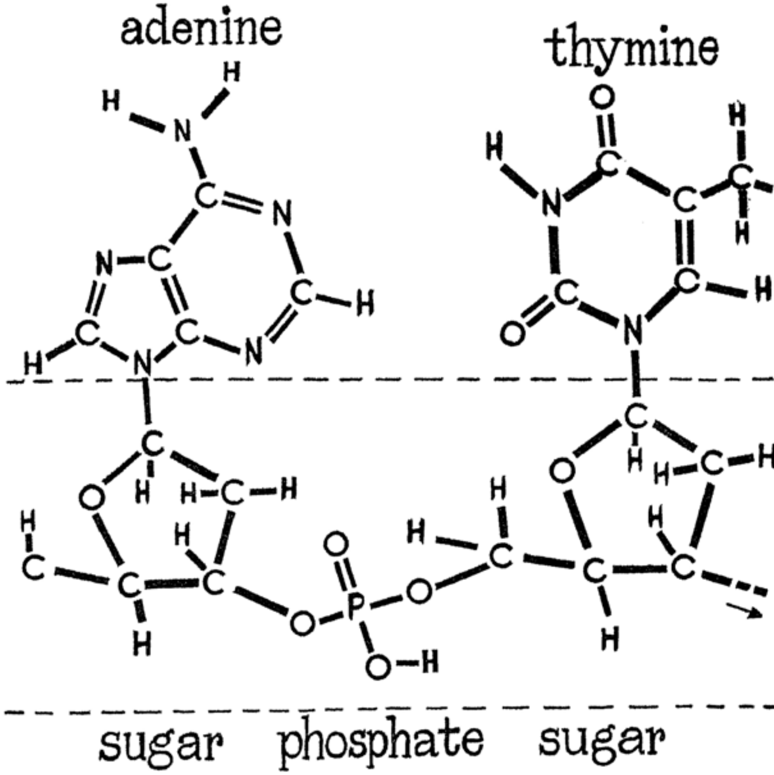
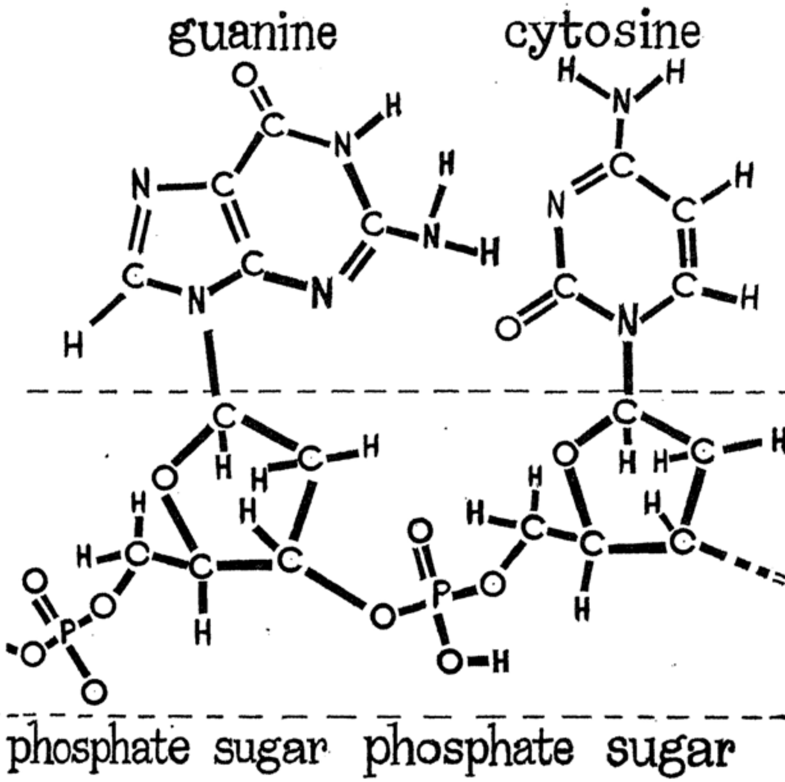


FIG. 6. DNA MOLECULAR

One scheme of the lay-out of molecules (and their
C = carbon atom, O = oxygen atom, H = hydro
phorus atom. (It must be emphasised that the
is still not agreed upon, but is

Thereupon a question arises: now that we have indicated the process by which molecules immersed in a given medium can control the elements of that medium to create molecules like themselves, have we crossed the frontier of life? The standard answer, as we know, is that the mere function of self-reproduction cannot by itself be regarded as the criterion. In the mineral world crystals too are capable of self-reproduction.

Let us pause a moment and consider this. We all know the classic experiment which consists of the introduction of a crystal " germ " into a supersaturated solution of the same substance,



LAY-OUT

atoms) in a short section of the DNA chain.
gen atom, N = nitrogen atom, and P = phos-
exact structure of this complex form of matter
almost certainly on these lines.

to produce a precipitation of crystals from the solution. In other instances the phenomenon may be less abrupt, but it always has the same basic physiognomy: it is based on a medium, the constituent elements of which, no matter what their organisation is, have the same composition as the "germ". It is the role of the germ to create like structures in its proximity. Since it is not the germ that does the work of arranging the elements involved, what is this but another example of a servo-mechanism? The "germ" limits itself to prompting the work. That prompting certainly corresponds to the notion of a servo-mechanism.

However, what we are now considering is not merely this sort of servo-mechanism. It is something more, namely a process which increases order. If we look closely at the nucleoprotein which, *introduced into a given medium*, makes something of it which resembles itself, and compare this with the growth of crystals from a supersaturated solution, we see that we are now on a higher level. This nucleoprotein is accomplishing an act which is much more difficult than crystallisation. It is not content merely with arranging molecules which already exist (which is what the " germ " crystal does). It constructs new molecules, or rather, more precisely, it assembles complex new molecules from separate molecular parts. The organising action is altogether of a higher degree.

Nevertheless, the process still requires these separate molecular parts to be available in the surrounding medium, so that this must have a precise composition. The small self-reproducing unit of matter which we are considering here works only in a definite medium. Let that substratum suddenly be changed—this is bound to happen, because the medium is subject to all the physical and chemical influences of the surrounding world—and that is the end of this particular self-reproduction.

THIRD PHASE: ORGANISATION

This, however, was only a beginning. The process was automatically bound to be made more perfect by the appearance of order of a still higher level and the achievement of a stage intermediate between the self-reproducing particle and the surrounding medium. The substratum ceases now to be an ordinary element drawn from the medium, therefore existing only accidentally. Instead, it is conditioned by a servo-mechanism capable of guaranteeing its existence even when the surrounding medium changes. Such a condition is realised if the protein attached to the DNA controls the environment in such a way that it favours the conditions of self-reproduction.

This set-up extends the field of possibilities of self-reproduction, since variations in the environmental medium now still allow it to take place, which in the first case was not so. This makes it clear to us why, although *a priori* DNA can combine with any

protein whatsoever, the useful combinations, those due to " survive ", are those in which the environmental medium is subjected by the protein to precisely those servo-mechanisms which serve self-reproduction.

This consideration provides us with a first clear glimpse of the great road of evolution, which gradually introduces into the servo-mechanism functions all the possible factors of variation in the external environment in such a way that the stability of the substratum is ensured. Altogether, these functions constitute a whole universe intermediate between the fundamental portion of the living entity and the exterior world.

Such is the first machinery of self-reproduction. It would be easy to imagine its further development by supposing proteins of increasing subtlety struggling on an increasingly broad front against the hazard of the external environment, and uniting with DNA. But that is not at all the way things do develop. What does happen is in fact much more interesting. It is the appearance of a factor which makes possible an " automatic struggle " against hazard. It is the principle of the conjugation of several nucleo-proteins.

FOURTH PHASE: CONJUGATION

This indeed is the decisive phase. A certain number of nucleo-proteins unite and combine their capabilities, so as to be better able to act on their common environmental medium. They assure the over-all self-reproduction of the collectivity which they thus set up.

What we have to think of is a chain of DNA associated to a protein which has a servo-mechanistic control over the environmental medium tending to favour the synthesis of a compound from certain elements in the medium. Now imagine another chain of DNA becoming associated to a protein to create another substance. Then a third, and so on. Next, let us imagine the substances thus created becoming the units in an autonomous cycle of servo-control, the coefficient of which is greater than 1. Obviously, such a cycle would " revolve " of itself, till in the end, permanently and automatically, it began contributing to the association of nucleoproteins the matter essential for its self-reproduction. We have now passed from the phase in which

proteins themselves create the substances necessary for self-reproduction to one in which they control a cycle which automatically makes those substances. These proteins of ours associated to DNA have risen to a higher level, while the process has also become more reliable, since it operates in the framework of a greater variation in the environmental medium.

Of course in practice one has to envisage not one single cycle, but a series of cycles controlled by the proteins of various basic nucleoproteins. The totality of these cycles, however—become a very complete network with a terrifying interlocking of links—will draw on its outer environment to make the material necessary for the group to do its own work, these cycles all controlling one another to such point that one can speak of a perpetual reconstruction of the little society which they thus constitute.

Such is the process of development which leads us towards the first true living entities. Yes, we shall soon now reach the cell, with its nucleus formed of numerous genes, which are so many nucleoproteins, in other words, the culmination point of a long and patient work of organisation.

It is agreed today that the cell is the simplest form of autonomous living entity found. None the less, a very long road has had to be travelled from the nucleoprotein, considered above in isolation, all the way to this set-up of a sort of community, with its group of nucleoproteins, all resulting from the process of development we have sketched out.

The road from the nucleoprotein to the cell is as long as the subsequent road from the cell to man is to be. The history of the metazoa, in which we first see a number of cells united in their joint interest, each one assuming a particular function, repeats on a superior plane, then, the history of our nucleoproteins associating to create servo-mechanisms which ensure the automatic supply of the raw material required by this first small society.

ATOMIC LANGUAGE

There is one fact, however, which disappoints. Very soon the cycles governed by nucleoproteins assume great complexity and we are no longer able in so concrete a manner to follow what happens.

Thus forced to consider matters in the abstract, we would, however, at least like to suggest a suitable language. Now, what happens? We have already spoken of the factor of self-multiplication of cycles, pointing out that this can be either less or more than one. Clearly, the situation will be very different in these cases. Indeed, if it is less than one, we have, properly speaking, not got any cycle at all. We have merely servo-mechanisms unable to develop. If on the other hand the factor is greater than 1, the cycle is maintained and we can speak of a real function of control, one proper to a living entity.

This exposition at once suggests the reactions in an atomic pile, and here I think we certainly have at our disposal a very useful logical model. Some years since, I pointed out that there was a parallel to be drawn between the cycle of biological control reactions and the chain reaction by which an atomic pile maintains its activity. I propose to take up the comparison again. In *Horizons of Atomic Energy** I suggested in 1948 that the concept of chain reaction went further than the mere framework of purely nuclear reactions, and constituted a phenomenon which broke away from the standard laws of physics. It had proved most useful in the development of my own conception of cybernetics.

In simple outline, here is the argument. In the well-known chain reaction of a uranium pile one has a huge block into the interior of which, as raw material, one has introduced a fissile body (plutonium or uranium 235) together with a " nutrient " (in practice uranium 238 is the commonest). The solution originally adopted for furnishing both these materials was simply to use natural uranium, which is a mixture of uranium 235 and 238.

The following process then takes place. The reaction started, the nuclei of the fissile material are bombarded by the atomic particles called neutrons. These make them explode. They produce debris, known as the products of fission, and neutrons. These fresh neutrons bombard other fissile nuclei, to produce further similar explosions. This is the process underlying the chain reaction. The new neutrons also bombard nuclei of ordinary uranium, which they turn into still further fissile nuclei by turning the uranium atoms into plutonium atoms.

Today, when the amount of fissile bodies made in this way

* i.e., the French *Horizons de l'Energie atomique*, Calmann-Lévy, Paris, 1948.

inside a reactor is equal to that consumed to keep the chain reaction going, such a battery is known as a "breeder". When a pile has become a "breeder", it can go on indefinitely, provided from time to time it is fed with new supplies of ordinary uranium.

Such a pile, however, does even more than that. It can produce more fissile bodies than it uses up. This is *a priori* possible since fission frees more than two neutrons (on the average, using plutonium, 2·7). One of these neutrons keeps the chain reaction going, the second restores the atom of the fissile body which has just been consumed, while the remainder enables the manufacture of an excess of fissile material which can be stored. When there is sufficient thus stored up, it can form the nucleus of a new pile, which can gradually break away from the mother installation to become a new, autonomous pile. This in turn can be self-reproducing, again on condition that it is fed with the necessary raw material, namely, uranium.

This process of development does indeed offer a very general picture of self-reproduction. The parallel with biological mechanisms is obvious. It is also most instructive to reflect on the way in which an atomic pile can be poisoned, just as a living creature can. For, as we have remarked, it is feasible for the chain reaction in a properly fed reactor to go on indefinitely. This assertion, however, calls for some qualification. The explosion of a fissile nucleus, as we have noted, gives rise to "products of fission". These are real corpses, and their mere existence proves harmful to the pile, for what do they do but absorb a number of neutrons which are thus lost to the chain reaction! Thus gradually, unless the products of fission are constantly removed, they grow in quantity, and neutrons are progressively lost, till, by the steady decline in the factor of multiplication which this brings about, the figure of this drops below 1—*and the chain reaction "goes out"*.

But this is just the picture that biological phenomena present. As waste accumulates in the heart of matter, the factor of multiplication of the self-reproducing cycles drops, till it falls below 1, and death ensues. Indeed, it would seem as if one ought to be able to lay down a functional multiplication factor for the entire individual.

Here it is interesting to recall Lecomte de Nouy's work on the speed of scarring of wounds, for this speed seems to be a function

of some such factor of multiplication of the individual. It takes the form of a " physiological constant " of healing. For, whereas in a patient aged ten we may see a wound area heal in ten days, fifteen may prove necessary at twenty, twenty-seven at forty, forty-eight at sixty. As age increases, the figure tends to infinity. This looks very like suggesting in biological cycles a decreasing factor of multiplication which eventually falls below 1.

Let us observe, however, that death is not unavoidable. Theoretically, it would be sufficient if we could collect and drain off the products of fission for a pile fed with uranium to go on functioning indefinitely. Similarly, in the world of life we do see cells which multiply by mitosis, able, apart from accidents, to live on indefinitely, " immortal ".

Were such favourable conditions to be provided, the characteristic of living matter would be to proliferate exponentially, the amount of living matter growing just like the power of an atomic pile with a factor of multiplication greater than 1. For that matter, there have been well-known experiments made with the " indefinite " culture of living tissue, the outstanding being those of Harrisson and Carrel, working with animal tissues, the most spectacular being Carrel's own very lengthy preservation of a chick's heart in a specially adapted medium. The survival of this seemed to be unlimited. Had growth been absolutely unlimited, the volume would in time have exceeded that of the earth. Here, the servo-mechanism power was biologically capable of being exercised on unlimited quantities of matter.

The closed culture of paramecium is just as interesting. Here one rather soon observes intoxication of the medium, in correlation with degeneration of the individual creatures. They become smaller, their movements slower. But if the medium is renewed, by moving the paramecium to a new infusion, the species procreates without any sign of ageing.

Here come in all manner of reflections on the expansive nature of life. In the absence of metabolism (in the sense of self-poisoning by the very products of life), or of other external limiting factors, living creatures seem to be capable of proliferating at tremendous speed. Cases are known of microbes which in a matter of months could cover the whole surface of this globe. It is not rare for swarms of locusts to occur so large that their total number threatens

to exceed that of the whole human population of France (43 m.).

Of course, our comparison with the atomic pile is no more than a comparison. None the less, it does furnish a handy scheme for the analysis of phenomena which depart from standard physics. In biology, however, the substances and phenomena are obviously totally different in nature. We certainly do not think that nuclear phenomena are to be seen in the biological world, except in very special cases, such as the destruction of genes by radiation. Above all, it is plain that when we consider the living entity, even at monocellular level, one cannot speak merely of "a cycle" of controls. There are numerous cycles. They form a network with cross-interlocked links, so that the same substances may even play a part in more than one cycle of servo-control at a time.

Nevertheless, the comparison with the atomic pile remains a valuable one. Just as in the case of the pile, here too we can distinguish the "critical conditions" below which any cycle ceases to work, and the way it can come to sudden life as soon as those conditions are again present. Similarly, in biology too we can suddenly find ourselves faced with an entity endowed with a new function when in it, in sufficient quantities, have been created substances liable to set up a new cycle of servo-control. Such starting-up can take place when a cycle produces an excess of material (compare the atomic pile which, when the reproduction of fissile materials is assured, at once creates these in excess) or, in more general terms, when a number of cycles each produce an excess of substances, the new substances, when available, automatically setting up a new cycle of servo-mechanisms the moment the factor of multiplication is superior to 1.

It is of interest too to observe the conditions in which new cycles may thus supervene. Principally, we can note:

(1) the stopping up of an existing cycle, which may liberate a substance which previously was only available in too small quantities;

(2) a change in the internal environment, which arises when richer nourishment becomes available in such measure as to increase the factor of multiplication of an initial cycle sufficiently, or even, more simply still, which arises from

the " functioning " of the living entity which, having called on a function to a considerable extent, has drained a so much larger quantity of material in one cycle that the by-products can set up a new cycle.

These considerations are all of extreme importance, for they are going to make it possible for us to indicate the great principles governing adaptation, that is, transformation of the living entity according either to its work or to changes in its external environment. We can also guess the answer to be given to two cardinal questions. The new means of the entity are acquired by the fact that living matter has this servo-mechanical power, by which, to an aggregate already organised, it is able to annex additional cycles corresponding to as many new functions. Apart from this, among all the cycles capable of appearing, those which are useful are added to a species by the play of selection.

We shall now very soon be able quite concretely to apply our thought to the machinery of evolution.

LIVING MATTER KNOWS NO FORMULA

What may more than anything else have puzzled the reader during the preceding argument is that we have outlined the machinery of life without any definition of the exact chemical make-up of the matter which enters into the cycle of servo-actions. We have not even suggested what the entity's structure is (I leave that to the following chapter). The furthest we have ventured has been to mention in passing the name of DNA—deoxyribonucleic acid—as the basic self-reproducing substance. Apart from that, we have restricted ourselves to speaking of " cycles " of servo-mechanisms, without the slightest definition of the exact nature of the substances which play a part in those cycles.

The omission, of course, was deliberate. The argument has been shaped in order to bring out what seems the cardinal fact: the living quality of living matter does not reside in its chemical nature. It is to be seen in the existence of those famous servo-mechanisms. It is these which are responsible for life's process of organisation and re-creation of matter.

Yes, it is essential to grasp that we cannot pretend to speak of any chemical " formula " of living matter, in the way that we give any precise organic compound one. First, because living matter is in a constant state of transformation. Still more, because the nature of the " matter " (the raw materials) capable of joining in any living cycle of servo-mechanisms tends to be indeterminate. It is only the basic part of the living entity which must have a precise chemical structure, that which is responsible for self-reproduction. Apart from this, all that is required of the substances constituting living things is a general " physiognomy " corresponding to certain conditions of resonance. This physiognomy is not unlike that of ourselves. There is a general scheme: we all have two eyes, a nose and a mouth. There is infinite individual variation: the shape of those organs and their relative positioning varies slightly from one being to another.

This applies equally well to the most primitive living matter and to that which today composes the most evolved living entities. Apropos of this, we have already noted that one cannot, for instance, speak simply of " insulin ", as if it were one substance. The composition of insulin varies slightly from one species to another.*

Here we may note an interesting attempt made by Pascual Jordan to get some idea of the general laws governing the set-up of living matter. The point is that for some time biologists have been intrigued by the fact that the weight of the protein molecule of various substances is often a multiple of 17,000.† Studying the haemocyanines, Jordan produced a geometrical hypothesis based on the notion of hexagonal groups of six amino-acids, the molecules being in a number of layers. The thickness of such layers, he

* In any case, these highly complex, heavy proteins present more than one problem.

† Reference may well be made also to the very recent work of Ping Yao-Cheng, of the Rockefeller Foundation Virus Laboratories, New York. He has drawn attention to the astonishing constancy of the percentage of ribonucleic acid in various organic substances, both animal and vegetable. This certainly is suggestive of the idea of some sort of basic unit common to them, that is to say, some sort of structure involving a precise number of molecules with given architecture, this being a sort of functional factory. The remarkable thing is that this unit quantity is exactly the amount of the ribonucleic acid isolated from the tobacco mosaic virus. Ping Yao-Cheng's conclusion is that there must be some machinery of formation of this unit which is the same in viruses, plants and animals alike.

postulated, was the product of a power of 2 and a power of 3. This means that the number would be somewhere in the series: 2, 3, 4, 6, 9, 12, 16 . . .

These suggestions of Jordan's are certainly interesting by their bringing into relief the physiognomies of proteins in various classes of similar substances (e.g., myoglobin, myogene, catalase, peroxydase), showing how, given a certain chemical function, proteins have formed on the basis of that function with the same general aspect. A very typical case is that of the series formed by haemoglobin, chlorophyll and vitamin B12. Haemoglobin is a protein structure founded on an atom of iron, the role of that element being to absorb the oxygen drawn into the lungs and convey it to the various cells of the body. But chlorophyll and vitamin B12 are of very similar structure, except that one is built around an atom of magnesium, the other on an atom of cobalt.

One thing is clear: it is all solely a matter of *structures*. With a molecular weight of merely 68,000 (comparatively low for proteins), a protein involves no less than some 500 amino-acids. As we have already said, the diversity of feasible forms is so enormous that it is unthinkable that there should be " a formula ". With greater logic, we should perhaps imagine a frieze consisting of some dozens of amino-acids in a pattern repeating itself with slight variations. The fundamental, here, is the basic theme. The parameters of the various variants define their various qualities. The forms of such variants, however, are so numerous that, even in the case of so common a substance as haemoglobin or albumin, one must assume differences not merely between one race and another, but even within a family or in one and the same being. The number of possible haemoglobins is itself so high, for the reasons I have developed above, that perhaps one should conclude that even in the series of haemoglobin molecules of one and the same living creature, where one can hardly help supposing it is a general type that is involved, one should nevertheless assume an aggregate of quite individual specific elements. The fact is, every single person we meet is *a priori* made of matter which is not quite the same as our own.

The fact is, so long as the parts of which it is made obey servo-mechanisms where they should, for the mechanisms of life the nature of the matter is to a certain extent of secondary importance,

and this can even apply to considerable changes of nature, provided that the conditions of the basic reactions are respected. For instance, as Dr. David Greenberg's experiments show, one can, remarkably, replace the calcium in the bones of rats with strontium, without the animal's appearing to be in the least affected.* Hence in the world of living things we have to take note of the great diversity of the substances forming various individual living things.

Indeed, even if we take the simplest of living entities, how can we fail to be struck by the fact that their matter is different, since it is their privilege to be able to " assimilate " elements from their environmental medium. We use the key word here—assimilate—too frequently without thought of its astonishing meaning. For what indeed does it mean? Not merely " take in ", but much more precisely, " make something like oneself ". Placed in the same environment as a flagellate, from that medium the amoeba will fashion amoeba protoplasm, while the flagellate manufactures flagellate protoplasm. After all, this is surely as much to be expected as, when two children are given identical meccano sets, one should make a crane, the other a chair. Indeed, our attention cannot be too closely drawn to the fact that the characteristic of life is not so much what elements it uses, as what servo-mechanisms it uses, and their specific purposes of arranging substances in particular cycles.

THE SYNTHESIS OF LIFE?

All these reflections seem to demand a hypothesis. Above, we showed how the synthesis of hormones was possible and had been effectively accomplished. Are we not also to conclude that servo-mechanisms should be feasible which, given the requisite raw materials, would work of themselves? This indeed amounts to saying that one would be able to assemble the necessary elements and make living matter artificially, in other words, that the synthesis of life is now within our reach.

There can be no doubt about it: we should consider the synthesis of life possible. We need, however, to define the requisite conditions, an assertion which certainly looks like a revival of the

* Provided, of course, that the strontium has not originated from a nuclear bomb " test ".

debates of last century about spontaneous generation. Ninety-eight years ago, when Pasteur published his replies to Pouchet's claims, there was a battle royal of argument. In the end, in 1877, Pasteur triumphed, disposing of the final objection of one of his most redoubtable adversaries, Bastian. What the great scientist succeeded in proving was that if one took all necessary precautions—in particular, if one used fired flasks, preliminarily raising their dry walls to 180° C., one could not hope to see bacteria, let alone any more complex living entity, develop in any insulated medium whatsoever, left to itself. Are we now going to throw doubts on that result?

Not at all. The protagonists of spontaneous generation make us smile as much as ever by their naïveté in ever imagining that so complex a thing as living matter could be born by magic.

The hope of creating life merely by sticking together some substances made of carbon, hydrogen, oxygen and nitrogen is an illusion just as much as that of the alchemists of the Middle Ages, with their hope of turning lead into gold in their crucibles. The chances of seeing life appear from an assemblage of atoms are of the same order as those one would have of getting a watch merely by establishing the chemical composition of the parts of one, melting a quantity of the given metals together, and letting the mixture cool. It is as silly as to expect an atomic bomb, exploding on a metalliferous mine, to transform the ores straight away into an electric power-plant. The probability of such things happening is in fact as near nothing as the chance of thus transforming an assemblage of atoms into a living creature. In this sense, Pasteur was absolutely right in his stand against those who assailed him. Their alleged experiments with spontaneous generation were merely the fruit of crude errors.

Unfortunately, however, Pasteur's results were soon given far too absolute an interpretation. The real reason, of course, for the violent check to attempts to synthesise living matter was that the would-be experimenters were ignorant of the *organisation* of living matter. The general conclusion therefore came to be that what distinguished animate from inanimate matter was some sort of vital fluid. Even Pasteur went so far as to produce the hypothesis—today defensible by nobody—that life had always existed on our earth, had indeed been here prior to matter!

In short, there began to be much too much thinking in terms of imaginary fluids, an approach which frequently took both biology and medicine far up the garden path. It was this state of mind that was responsible for the failure to recognise the importance of the work of Claude Bernard, whose cybernetics today appears as the great triumph, for in masterly manner he at least did perceive the circuits of servo-mechanism and self-regulation which we are now able to analyse.

Today, as we are getting to know the physiognomy of the utilisable proteins and that of nucleic acid, the synthesis of life appears in a totally new light. The problem now takes the following form: supposing that from amino-acids (which, as we know, can be synthesised directly from substances composing the earth's initial atmosphere), we succeed in making both this nucleic acid and proteins, and supposing these unitary parts are brought into contact with each other, is it conceivable that life, however rudimentary, would then automatically appear?

It would seem that the answer to this question has already been half given by experiments made during 1955 on the tobacco mosaic virus. It is these we must now consider.

THE SYNTHESIS OF A VIRUS

Tobacco mosaic virus attracted a great deal of attention as much as twenty years ago. By now it has acquired the " nickname " TMV (See Plate IV (ii).) In 1935 the American chemist Stanley (later a Nobel Prize winner) succeeded in precipitating a substance which seemed to be a curious half-way house between living and inanimate matter. Like inanimate matter, it crystallised. But, despite this, it still kept its power of multiplication. It also continued to contaminate the leaves of the tobacco plant.

In due course, Stanley gave a description of this virus. It seemed to be a pile of some 2,800 layers of sub-units, with molecular mass of upwards of 18,000.* The total molecular weight was 40 plus millions! This was much greater than that of the " ordinary " proteins.

Systematic analysis of the structure of the virus was to follow. Working in the magnificent laboratory of the University of

* Cf. p. 124, discussion of unit of *c.* 17,000 molecular weight.

California on the top of Berkeley Hills, Stanley succeeded in analysing the thing's strange anatomy. He demonstrated that the protein formed a series of helices, resulting in the over-all microscopic model of a tree-trunk. There was this hollow-centred cylinder, in the free spaces of which nucleic acid was present in the form of filaments. The whole was very like a hollow trunk with twigs growing across it inside. Examination by more than one method confirmed this picture.

Now, last year, in the same laboratory, under Stanley's direction, an experiment of extreme importance was attempted. Two chemists, H. Fraenkel-Conrat and R. Williams, set to work to pull the constituents of the tobacco-leaf virus apart, *then to put them together again*, to find out if the reconstitution produced a virus which was still active.

The detailed report of this operation was published in October 1955.* The investigation explained in detail how they could be sure that the breaking-up of the virus molecules was complete. The virus was first hydrolysed,† then the untouched residue was separated by centrifugal methods, after which ammonium sulphate ensured precipitation of the protein. But when this nucleoprotein had been rebuilt from its broken parts, after about an hour, although it was now much feebler than before, the activity of the virus reappeared.

Of course, the objection may be raised that, however thoroughly one tries to dissociate the virus, this is really not completely accomplished, so that after the rebuilding process, when tests are made, and infection again results, this comes from viruses which had never been broken up. This objection, however, Fraenkel-Conrat and Williams disposed of very satisfactorily. First, they effectively showed that the dissociated protein solution did not contain more than one part in a million of undestroyed virus. Then they showed a measure of the infectiousness of the reconstituted virus (admitting this to contain one part in a million of undamaged virus). This renewed infectiousness was about one-tenth that of the original virus culture. Hence, were this subsequent infectiousness to be ascribed to the portion of virus which had not been dissociated (one-millionth part), one would have to make the

* *National Academy of Sciences*, Vol. 41, No. 10, pp. 690–698.

† Subjected to initial break-up in solution.

paradoxical assumption that the process of dissociation had actually increased the infectiousness of that one-millionth portion of virus which was not touched to several hundred thousand times what it was before, obviously a ridiculous conclusion. It was therefore quite satisfactorily demonstrated by Fraenkel-Conrat and Williams that, having broken down a virus, it was possible to put it together again.*

The present aim of scientists in this field must now surely be clear. It is to realise the synthesis first of nucleic acid, then of protein matter, and after that to see if by putting the two together we can make a virus. If we succeed, we shall have succeeded in creating a virus from organic matter. As far as the tobacco-leaf virus goes, the above experiment did at least serve to give us our first hints regarding this protein: its spectrum proved to be very like a mixture of tryptophan, tyrosine, cysteine and phenylalanine. This observation, however, is far from telling us anything more about its structure.

It would therefore be a bold step indeed to make prognostications on the time which may prove necessary for achievement of the complete synthesis of living matter. It is indeed no simple task, to propose to repeat in the laboratory a work which it took nature many, many million years to work out. Nevertheless, it seems beyond doubt that this experimental work is in the logical path of biology as this science advances. *A priori* we should now believe the synthesis of life feasible. Or, at least, of life in that very elementary virus form which we have been considering.

And with what philosophical consequences? That is a problem which it will be the task of our final chapter to answer.

* To refer back to our earlier comparison, this experiment is after all very like taking an atomic pile to pieces. If one does so, the chain reaction automatically ceases. One can then leave the parts for a longish time (of course, on condition that no metallic corrosion or other outside cause is allowed to deteriorate the metals in the meantime) but when one puts them together again, they will work again.

CHAPTER VI

The Machinery of Evolution

WITH the means at present at our disposal, the synthesis of a virus is a tremendous undertaking. But set against the vastness of the world of living things, it cannot but seem very trifling. Some scientists, indeed, question whether viruses even have the right to claim to be living entities. They cannot " live " at all except as parasites of more highly evolved matter, which provides them with substances which they cannot make themselves. But there is certainly nothing which should lead us to assume that our modern viruses are the same as any which existed on earth at the dawn of life. Such initial viruses were certainly able to find adequate nourishment in the mass of organic matter already synthesised. Ours may therefore be regarded rather as their degenerate descendants. For in the light of what we positively know of the chemistry of organic matter, it seems but reasonable to assume that, prior to the evolution of the cell, the primitive life of our earth first went through a virus stage.

This is certainly the standpoint adopted by biocybernetics. The process of development has been outlined in the previous chapter. The first appearance of living matter on this earth took the form of cycles of servo-mechanisms controlled by nucleoproteins. In other words, life began with the birth of viruses. To reach that conclusion, we have merely argued logically. Taking account of the chemical properties of matter, servo-mechanisms were automatically bound to develop in this way. In the beginning, the vortex of servo-cycles which arose automatically became a process culminating in viruses. And if here anyone feels baffled, disappointed, that after so much argument, ranging over so many millions of years, we have still covered so little of the history of

life that we have only reached substances on the borderland between inanimate and animate aggregates of atoms—if some dismay is felt that most of life's development is still ahead of us, still unexplained, there is on the other hand at last a positive answer of optimism and encouragement which can confidently be uttered. Here, at least, an important line can be drawn.

From now on, we do know the rules of the game. Or, at least, we have the elements of knowledge from which to obtain them. This history of life has now at last assumed the more simplified form which the mathematician obtains when he reduces his equations to the manipulation of numbers. For we already know that this basic image picture of the self-reproducing nucleoprotein which is the soul of the virus is also to be that of the "key parts" of all other living entities. We have already examined the way in which the nucleoproteins eventually associated together, jointly to control the cycles of servo-mechanism which serve the "communities" they thus form. We see the living entity as a grouping of nucleoproteins in command of increasingly complex machinery. And this now directs us towards the standard distinction to be made in the case of every living entity.

We are obliged to discern two parts, which are called the soma* and the germ. The germ essentially consists of undying sexual cells which are transmitted from one individual to another, and constitute the key part of the living entity. The soma is no more than a machine which the germ builds and uses to assure its own reproduction. In the germ we always find a programme of development for the organism. Moreover, this programme is always based on the same formula. That is to say, it depends on the conjugation of nucleic acids and proteins.

Thus in every case it is the nucleoproteins that are the principal parts of the living entity. It is differences in their architecture which result in utilisations of the environmental material to manufacture this or that virus, bacterium, animal or plant. The "programme" or "plan" of flea, lion or shark is drawn up on nucleoproteins which have basically the same structure and to which, in one creature or another, are added certain variations.

Thus, starting from a single nucleoprotein controlling a minute

* Greek *soma* = body.

aggregation of molecular machinery, a tremendous evolutionary process was bound to unfold, a process the purpose, the *why* and the *how* of which, I tried to define in my opening chapter.

THE SENSE OF EVOLUTION

In order with increasing efficacy to wage the battle against chance, the mechanism constituting the soma gradually assumes ever greater dimensions. While the germ remains an assemblage of molecules invisible to the naked eye, the soma becomes a structure the dimensions of which, in comparison with the germ, become fantastically great. Further, by the mere fact of their development, the functions of this soma become ever more complex. In the end the soma is to develop to the point of being able to manage itself, that is to say, to struggle against chance in order at all costs to ensure its own maintenance and support.

Another way of putting it is this: starting from the formula of a self-reproducing molecule, what life does is build on to that molecule ever more numerous " accessories " aimed at " conditioning " the way it gets its nourishment from its external environment. Thus the core of living matter has a double role. First, it has to see to the reproduction of itself from the elements available to it. Secondly, it has to supervise the construction and regulation of the automatically self-reproducing living factory which is specifically fashioned so as to play the part of intermediary between the germ and the outer world.

The germ may therefore be compared to an engineer who is quite alone at the outset, obliged to do everything himself, but who later groups about himself a little team of men to whom he can confide a number of functions. His own function then becomes that both of giving his workmen their work schedules and of making sure of a continual flow of new personnel. In a later phase of development, the initial team of assistants in turn " make the grade " into shop managers, who themselves take on whatever new hands are required and allot these their work schedules, and so on and so forth.

Such is the set-up in the living entity: the total outline is one of a systematic hierarchy. At the top are the nucleoproteins, who order the manufacture of the substances which we call enzymes.

Next below the nucleoproteins are these primary enzymes, and by the processes reviewed above they build up the raw material which they acquire into a stratum of secondary enzymes, these by the same mechanism giving birth to a third level of enzymes, and so on and so on.

Here we clearly get the notion of a series of " strata " which form a real transition in the living entity between the exterior world and the most highly organised part of the entity. And the construction of these layers is determined stage by stage along the lines of the programme laid down by the key nucleoprotein.

This idea of the set-up fits in with the ideas of a number of biologists, notably of Bensley and Whipple, who tend to see the various elements which enter into the constitution of the living entity as a hierarchy.

Here an interesting series of experiments serves as additional proof of this. It has been established that certain proteins can be extracted from cells without apparently causing them any damage, whereas when others are extracted, though the essential functions remain unchanged, the appearance of the cell changes. The extraction of yet other proteins results in complete destruction of the cell. The explanation of course is that the removal of enzymes of inferior order is relatively unimportant, since such enzymes are automatically resynthesised by the higher-level enzymes, whereas the removal of the top-level enzymes brings about paralysis of the whole apparatus.

In conclusion, our logical analysis gives us a warning. It invites us not to see in this association of enzymes anything more than the assembly of increasingly efficacious means of affording our nucleoproteins the possibility of reproducing themselves in an environmental medium liable to an ever wider range of variations. And when these means to adaptation to environment assume the stature and the perfection of an animal or a plant, the principle is still the same. The individual living thing remains no more than the means the nucleoproteins have devised for the attainment of their aim of self-reproduction.

This view may disconcert. No doubt it will remind the reader of Samuel Butler's famous wisecrack that, to eggs, hens are merely the means of making other eggs. But so far this certainly is precisely the sense we are obliged to see in life! Simple or

complex, the animate individual (plant or animal) is the gene aggregate's means of reproducing itself. We should, however, be wrong to let ourselves be deceived by the humorous twist Butler deliberately lent his observations. I have elsewhere emphasised the great value of the writings of that provocative thinker. They contain many a remark which is truly prophetic. Samuel Butler was a strange spirit, too little known, indeed. I would surmise that his name will in the years to come be quoted more and more. A century before our time, therefore knowing nothing of the wonderful work of science which is familiar to us—indeed, with only Darwin's theory to start from—Butler put out ideas of remarkable pertinence about the " evolutionary machinery " of the history of life.

THE WHY OF IT

But we still have to see why such an evolution is the one which logically took place. Even granted that, given the constituents of the world in its primitive stage, cycles of servo-mechanism appeared which finally yielded those knots of concentration which we see as self-reproducing nucleoproteins, which themselves are linked to cycles, why should we suppose that these nucleoproteins will prove to be the nucelus of an ever more developed organisation?

As a matter of fact, I did offer a generalised explanation in my introductory note. There it is pointed out that order tends to permit the creation of agents which create still greater order, the process being potentially able to increase indefinitely. What we now have to consider is the actual way this was accomplished, the process of selection of proteins conjugated with nucleic acid.

For look closely at the nucleoprotein set-up. The proteins govern cycles which make enzymes from the environmental raw material, or, rather, from certain given substances in this. It is clear that were this raw material always to be of the same composition, and the physical and chemical conditions of the environment did not vary, while the cycle only recruited a single precise substance, everything would remain unchanged.

In practice, however, it is not at all like that. Particularly if we consider the factor of nutriment, things are complex. It is illusory to imagine a cycle which would restrict itself to absorbing one strictly defined substance from its environment. We know,

anyway, that our servo-mechanisms are essentially based on the phenomenon of resonance. The molecules which come into them are thus those which have a definite physiognomy, though these may arise from chemical structures which are slightly different.

This observation applies above all to the early stages of life, in which the highly differentiated molecules which we find in higher forms of life were still not in existence. The specificities involved are thus to be understood in rather a broad sense. Consequently, it is practically impossible for an enzyme which exerts a servo-control on a given chemical substance not to be slightly deceived, and equally well to accept some other substance, providing this has in it those traits which trigger off the respective servo-mechanism. In any case the traits in question will be summed up in a limited quantity of data.

This problem of specificity is to some extent suggestive of the automatic mechanism of the slot machine. The machine admits only coins which are of prescribed dimensions. Very well, but is there then not every likelihood of some other coin or counter having the same dimensions and doing the trick? Certainly there is, but this undesirable eventuality is guarded against by a tiny balance which enables the slot machine to take account not only of the dimensions of the coin inserted, but also of its weight. Of course, a mere counter would still work the slot machine if it had the right dimensions *and* weight. In practice it is scarcely worth while anybody's contriving this. But were it very easy to do so, it would not be at all difficult to introduce yet another servo-control in the machine, and another. The list of check controls is, however, ultimately limited by practical considerations. No slot machine is absolutely proof against all fraud.

This is precisely the situation with our cycles of servo-control regarding the raw material of the exterior world. That raw material is most varied. Whereas in our prologue we could visualise the fluid medium of the initial earth as in the main consisting of four fundamental elements, the real situation, which has to be taken account of in any more profound study, is that side by side with those four V.I.P.s (carbon, oxygen, hydrogen and nitrogen), we have some dozens of others, all of which are capable of entering into the most varied combinations and also of combining with

organic bodies, to form such numerous series of compounds that nobody has ever even thought of trying to estimate their total number.

Thus what happens in reality is that every enzyme absorbs a large collection of substances, the composition of which varies constantly with locus, climate and neighbouring forms of life. As various substances are admitted to a cycle, a process of natural selection automatically begins. Among the bodies of slightly differing composition which are now formed, there will be some that impoverish the cycle, reducing the multiplication factor to less than 1. In the case of elementary forms of life that will settle the matter, these individuals perish.

On the other hand, there will happen to be other substances which will raise the multiplication factor. This will result in spare matter, destined for incorporation in a new cycle, which will start up by the process already outlined. Such new cycles are born spontaneously as soon as the critical conditions are exceeded, that is to say, as soon as the substances present have a composition and a density such that they enter into a servo-cycle the multiplication factor of which exceeds 1.

At this point, a new gene is created in the self-reproducing system, while the substances in question definitely form a part of the living entity. Thus, we may note in passing, we get the explanation of why certain organisms systematically retain various metals or non-metals. For instance, the copper in the sea concentrates in shellfish, which gives them their characteristic blue blood, whereas higher creatures have red blood, because this (in the red corpuscles) retains iron. In like manner there are brown seaweeds in which gold accumulates, oysters with rubidium, corals with lead.* These various elements are the starting-points of definite chemical functions, a matter which always has to be considered in the structure of any living thing.

In all this work of selection, clearly one cannot speak of an animal's "tendencies". That is not how evolution proceeds, but instead by the retention of favourable possibilities. Creatures which adopt unfavourable possibilities disappear. On the other hand, formulae which are advantageous by reason of the substances

* i.e., the blood of the coral-forming creatures contained lead where human blood contained iron.

which they offer or some new means which they create increase the chances of survival. Thus is shaped a movement in which we see two distinct phenomena which are in fact what yesterday were sometimes designated "minor" and "major" evolution. Minor evolution exhibits the progressive improvement of existing servo-cycles, that is to say, improvement of the organisation of an individual on a given formula. The term major evolution, on the other hand, must be reserved for the appearance of functions born whenever totally new cycles come into service. In the history of life, major evolution means the appearance of new genera and species after those apparent breaks in evolution which yesterday so puzzled the biologist.

At the same time, it becomes easy to understand how badly the notorious problem of the inheritance of acquired characters was formulated in standard biology, confronting that science with a very peculiar paradox. To make evolution possible, it used to seem obligatory for there to be inheritance of acquired characteristics. Had there been complete separation between soma and germ, that is, had the soma never been modified at all by the teachings of the germ, obviously living creatures would always have transmitted the same soma, which is equivalent to saying that there would have been no evolution. At the same time, there has been almost systematic frustration of all the experiments made in the attempt to show a species inheriting acquired characters.

In the light of our survey, however, it appears that the majority of those experiments were childish. For instance, after cutting off the tails of mice for some generations, experimenters were disappointed when mice were still born with tails, and those tails were not even a little bit shorter. Their investigation was really as if, by daily correction of the badly multigraphed address on one's newspaper wrapper, one hoped that after some time the addressograph in the newspaper office would get the thing straight. It is the basic nucleoprotein of the living entity that furnishes the scheme in virtue of which everything is subsequently constructed. The structure of the living thing is but the consequence of that scheme.

Is this to say that the germ-soma orders are one-way systems? No, not at all. As we have just seen, had that been so, living creatures would never have evolved at all. Therefore we have no

course but *a priori* to admit that there must be full two-way linkage between soma and germ. Apropos of which we may perhaps make an important point. Hitherto in our use of the idea of servo-mechanisms what we have presupposed is a primary system being able to impose its will on a secondary system, which means impressing on that system some order without thereby itself being affected. Yes, but that view of the matter was, after all, purely theoretical and schematical. In the physical world we are always either not linked or fully linked or coupled. It is understood in physics that there is always reciprocity of actions. Steady! you may cry; is this not to argue against my own thesis. Have I not emphasised as a characteristic of a servo-mechanism that a relatively small expenditure of energy in one cycle tips off the use of much greater energy in another cycle, and this dissymmetry amounts to direction of increased energy in a definite direction? In practice, however, this in the main one-way employment of energy never completely excludes all reciprocity. This is to say, the action thus " controlled " does involve some drain of energy from the first cycle. This after all should be clear enough from the examples of servo-mechanism which we have considered. Take that classical instance, the thermionic valve, the basic instrument of radio reproduction. The energy of the anode current is controlled by the potential of the grid, and in a popular course of instruction you may be told that the intensity of the grid current is to all intents *nil*. But that is only a first approximation. After all, that grid current does exist. It *is* a real current. However feeble it may be, some energy is in this way used up in the grid. It cannot possibly be absolutely nothing. After all, it is impossible to exercise a servo-action without some expenditure of energy, for the simple reason that the controlling signal must have its own physical existence, and quantum theory tells us that to exist at all this must reach a certain minimum.

If we consider the two systems formed on the one hand by the nucleoproteins, on the other by the totality of the living entity, we find ourselves bound to take account of action both ways. By far the preponderating action is of course the direct one, but in the opposite direction we cannot but admit that the nucleoproteins must have some response to the changes which take place in the rest of the entity. When that response is fundamentally disturbed

by the appearance of new servo-cycles, the organisation of the nucleoproteins themselves must be liable to quite profound transformation. And normally, modifications of any living thing are to be seen solely in structural details of the nucleoproteins, even though these do preserve their fundamental physiognomy.

This machinery suggests certain important biological laws:

(1) When a substance has been absorbed in a cycle, this automatically makes use of it, that is to say, the matter involved is no longer available for any other cycle. To put it in other words: when the living entity has selected a path, it is unable to turn back. It is for that matter significant that in the history of life one never sees the reappearance of a genus or an order which has once been extinguished.

(2) We can, however, speak of degeneration. This takes place when the living entity ceases to call on a function and the matter involved in that cycle takes part in some other cycle. If the factor of multiplication of the initial cycle falls below 1, the original function disappears, though its signal remains in the nucleoprotein. The situation is like that of an abandoned workshop. No workman is to be seen, but the building and all its tools are still there.

Thus in its very formula any living thing preserves a memory of the various preceding stages of the species. This makes it clear to us in a general way why, as Haeckel maintained in his celebrated axiom, the growth of any individual recapitulates the stages of development of its species. Haeckel put it that *ontogeny is a short recapitulation of phylogeny*.

The point, of course, is that the enzymes which at any given moment constitute the " last layer " of the living entity are in the course of any further stage of development the initiators of the synthesis of yet another cycle of enzymes dependent on them. Once any machinery has been acquired, the elaboration by the body of enzymes at any level automatically results in the formation after a longer or shorter period of time of a further stage of enzymes. And when we observe the living creature's development, we see that its various stages present us with a series of beings which have successive layers of enzymes, these representing successive forms which this species once had at these various enzyme strata. The enzymes

which are developed are never the same as those which went before, because they always have the additional ability of creating new enzymes of a still higher level.

THE STRUCTURE OF THE LIVING CREATURE

Now an important problem arises. So far, our analysis has shown how matter was able to engage in servo-cycles and form this surprising hierarchy of compounds. Yet is all this so suprising? Is it not merely one aspect of evolution? For do we not know that living things have assumed a certain form or structure which has its own hierarchical features? Admittedly, this at first consisted merely of an aggregation of numerous identical cells created by the reproductive activity of a given nucleoprotein. But later we find those cells assuming different forms, with both physical and chemical appearance very varied. This happens as soon as such functions as breathing and digestion appear. Certain cells harden, to form bones or carapaceous covering. Others give rise to remarkable elastic tissues. And, most remarkable of all, this great mystery is governed by its topological aspect—the way these various cells are distributed, and the striking laws which give organs their shape, their dimensions, varying only within small limits. However are we to explain this birth of a topological (or geometrical) sense in the living entity which thus, in the cilia of minute creatures, in fishes' fins, in the marvellous crystalline structure of the eye, furnishes us with a wonderful range of different substances, all with precise composition, precise form, precise location?

Undoubtedly these topological mysteries bring us back to the nature of the enzymes formed according to the programme contained in the nucleoprotein of the germ.

First consider the basic problem of differentiation. What at first sight could be more stupendous than the everyday phenomenon of the human embryo developing from a single cell? It may seem logical to us that this development should take place, and indeed *post hoc* we do feel quite able to explain why the original assemblage of cells should pass through the well-known stages of *morula*, *blastula* and *gastrula*. First the initial cell multiplies, thrusting out grains, till it looks rather like a blackberry, the *morula*. Next, the cells form themselves into a spherical ball-like

form, the *blastula*. After that follows the *gastrula* stage, in which the ball begins to look as if it had been punched in at one point, the indentation going to form the inner substance of the creature. Yes, but, all the same, what was there in those cells originally to tell us that they would thus evolve in many differing but specific ways, to form the incredible variety of kinds of tissue which make up, for instance, a human body?

We may put the differentiation down to the initiation of various new cycles of servo-mechanism and the curtailment of others. We know that the machinery of this differentiation is essentially to be found in the cytoplasm. For all the cells of any creature have the same nucleus. The same grouping of nucleoproteins thus characterises both individual and species. But though the nucleoproteins give rise to identical enzymes, the work of these varies with the medium and the number and positioning of the neighbouring cells. This is sufficient to explain the development of a variety of cycles of servo-mechanism, leading to the formation of various specific enzymes. Given this process, it is inevitable for differentiation to proceed further and become more marked.

The programmes of our cells might be compared to the identical multiplicands of a series of products, the multipliers being the environment, both the medium in which the cells are situated and that formed by all other neighbouring cells. What happens is that these multipliers gradually change. At first the products are more or less equal. Differences are limited to the units column, but soon enough the differences grow greater. They leap up to the tens column, to the hundreds, to the thousands, and so on. And when we remember that each figure represents an order in the hierarchy of enzymes made on the programme of the nucleoprotein, we have some idea how it comes about that with the appearance of new functions we get such great cell variety.

But though the multiplication of cells in any given zone of the embryo (or the checking of all growth) is thus governed as much by the nature of the servo-cycles proper to the given cells as by the development of neighbouring cells, it remains clear that in the last resort it is the nucleoproteins of the nucleus which lay down the " limits " of all these operations, everything being planned the moment that cell multiplication begins. The fact that the organs of the body automatically acquire their given shape may

still excite our wonder, but, by virtue of what we have just discussed, there is no question but that there is a precise correspondence between their form and the structure of the nucleoproteins. In other words, each living thing is definitely planned in advance in its initial nucleoproteins. This is the fundamental point which needs bringing out. Shortly, we shall learn how nature contrived to draw up such a programme.

But this is not all. Not merely is the topology of the body's parts all laid down in the germ nucleoproteins, but it is these very nucleoproteins which condition the manufacture of the enzymes which are able to start the processes involved, above all those complex movements which by the machinery which we all know as "instinct" the living animal will perform mechanically as soon as it is born.

It is easy to understand the movements which the various organs of a living entity can make. In inferior creatures they are in essence under the direction of enzymes. Movement here results from the change of form of certain molecules forming the tissue which moves. As for ourselves, today we know that the contraction of our muscles is fundamentally caused by a chemical transformation which results in a twisting of the fibres which constitute myosine, thereby bringing about a shortening of the molecules of this substance, the principal protein of muscle.

In other words, in these two cases, at either end of the ladder of evolution, mechanical energy results from a chemical transformation. True, in creatures of the superior orders this servo-control is also an electrical one, that of the nerve controls. But in either case movement is caused by the production of a given chemical. In other words, again a servo-mechanism.

Nor is this the most astonishing thing about muscle action. The most remarkable feature of it is that this muscle contraction and all the movements of the creature should thus be set going at the precise moment desired, so that the creature is capable of whole series of movements which themselves involve clearly formulated programmes of action.

How comes it that our hearts should work so impeccably, and without our ever knowing that they are doing it? How comes it that the moment they are born so many animals should know how to perform the most varied movements? Why should a

butterfly or another insect emerge from the pupa stage able to fly without any appreciable hesitation? These are all questions of a capital order and it is most regrettable that the academic biology of our schools should have been so largely unconcerned with them.

Just look at the butterfly's wing-beats! Just watch that spider juggling with its feet. Not only are these creatures performing movements which are actuated by micrometers under the control of complex servo-systems, but all those movements are beautifully co-ordinated. There is nothing haphazard about them. Nor can there be the faintest suggestion that the individual " works them out " every time. They are all automatic movements, just like our walking. The creature's responsibility is reduced to fractional adaptation of the basic action, as when we ourselves decide to direct our vastly more intricate ambulatory movements not in this direction, but that.

Here it is interesting to make a comparison with our most up-to-date techniques of programming the working of industrial machine-tools. Let us take a tool which is required to perform a series of operations, say: to reach out an arm, lower it, flex the end to face at right angles to a given plane, lower it to touch a sheet of paper, then actuate a suction device to pick up that paper, then move the paper and place it in position on a frame, then perforate the piece of paper in a precise place—and so on and so forth. To achieve such a tool we have *a priori* more than one solution.

Solution One. We might work out the time each of a number of separate motors requires to do its work and provide a distributor which will supply each in turn with current for the necessary time. This method, however, is as a rule rather unsatisfactory. We cannot fix the duration of each successive operation with sufficient nicety for the system to be practical. There are a number of factors which may always make this or that movement in the series take a second longer—or shorter.

Solution Two. We could adopt the same system, adding an automatic current distributor and a device to cut off the power from each operation only when the operation is completed. This is a fairly simple way out, one used in many automatic tools. It certainly allows for proper functioning of the machine-tool at each stage. But, unfortunately, it requires allowance for so

many dead periods between one operation and another (allowances, for instance, when any operation takes longer than it should) that it wastes a lot of time. It is not very efficacious because even when this or that movement fails to be made at all, through a breakdown, all other operations in the series are performed—quite stupidly. Such a machine might punch a non-existent sheet of paper.

Solution Three. Finally, we may do without a distributor altogether. This we can achieve if we so fashion our controls that the completion of each operation sets off the succeeding one. This is electrically feasible by fitting contacts which only come in when the immediately preceding operation is completed, but then at once sets off relays which switch the current off one task and on to the next one.

What is the solution selected by life? As you may have guessed, it is this latter one, which cuts out any central distributor and in no way depends on any revolving part, for the wheel device does not exist in living creatures. For that matter, nature was sound indeed in never adopting the wheel for any of its machinery, because no real link between a rotating body and its support is possible.

It is only the system of working by a chain of relays which avoids misfires. In this, every successive operation is delayed till the first is completed, however long—or short—a time may be needed. But this principle fits in wonderfully with the system of cycles of servo-mechanisms which we have suggested is responsible for all a living creature's functioning. "All" that is required in the living entity is a programme of action. At birth we see this come into operation in the form of instinctive movements. The only condition which is obligatory is that the accomplishment of any movement should produce the appropriate substance—the appropriate enzyme—to set off the next movement, whatever this may be. Learning here is reduced to such choice of substances (enzymes) as allows for the realisation of the given series of actions.

Here once again let me quote Samuel Butler. He did not hesitate to compare the virtuosity of a great musician with the ease with which animals walk, fly, and digest their food. And in this he was absolutely right. Just as our virtuoso's performance is preceded

by a long period of practice, during which he trains and gains strength from successive trials, in the last resort we must admit that animals acquired the substances which today govern all their automatic functions—particularly we think here of the enzymes which direct their programmation of movement—thanks to the training and trials of millions and millions of their forbears over millions of years.

Yes, that is the point: there must have been a time when even butterflies learned to fly, when animals learned to move their hearts and make their stomachs function.

Exactly the same applies to our reactions to variations in the environmental temperature. It is often thought that to establish heat regulation an animal must have a " notion " of temperature, or that to be able to see it must have a notion of light—or of sound, for hearing.

Nothing of the sort. The creature has no need whatever to " know " what temperature is, to react to that phenomenon. Take the following simple comparison. Suppose through an inspection window one observes sets of pipes in a sealed-off compartment. The pipes are made of various plastics. Some are more heat-resistant than others. As the compartment is sealed off, there is no means of knowing what the heat inside is. We have even no reason to suspect that the temperature in the chamber is at all high. All we do is observe that some pipes stand up to whatever the conditions are there better than others. Is it not clear that, though ignorant of the fact that it was heat which caused some of the pipes to break down, we should in future have all our pipes for use in this chamber made of the material which withstood whatever the internal conditions were? That would in effect mean that we had reacted successfully to the effects of higher temperatures without the least knowledge of what we were overcoming. We should merely know that " these pipes stand up to it " and " these don't ".

Such is the behaviour of living creatures as soon as they are able to observe the teachings of experience Without any need to know what those factors are, they become capable of reacting successfully to various factors in the world about them. They adjust themselves solely by reacting to the repercussions of those factors on themselves.

This is an approach which is worth thinking on. We should not forget that even man only " knows " factors of the outer world by the direct or indirect effects these have on himself.

GENE AND INFORMATION

It may be found astonishing that so small a thing as the aggregation of molecules of nucleoproteins which constitute the gene should be capable of " depicting " a living creature. The nucleoproteins direct the manufacture of the enzymes which in turn are responsible for making secondary enzymes and so on and so on, in the manner which we have been observing, and the integration of all these processes does certainly result in all the machinery, however subtle it may be, of the individual's functioning. All this, moreover, is definitely the work of the germ nucleoproteins alone.

One is likely *a priori* to be rather awed by the notion of so complex a programme being contained in so slight a volume, for the programme includes the nature of the substances to be made, their positioning, the form of the organs to be built up, their own specific programmes of growth, and their movements and action, which all amounts to a criss-crossing of control mechanisms between all the enzymes involved of a complexity which is indeed startling.

However, this indubitably is the position. Indeed, the quantity of information registered in the nucleoproteins staggers the imagination.

The chromosomes, the particles which embody heredity, are today very well known. They are to be found over the whole range of life. The number of chromosomes in a cell varies according to the species. Man has 24 pairs, the dog 39, the cat 19, the mouse 20 and the famous little *Drosophila* fly (the great " guinea-pig " of heredity research) 4 of them.

However, we should not think in terms of chromosomes, but of genes. For any chromosome is only a collection of genes. Each individual gene is one of the molecules of nucleoprotein responsible at the outset for the synthesis of one of the principal enzymes necessary. In the *Drosophila* fly, for instance, the total number of genes (in only four chromosomes!) is to be counted

in several thousands. When we turn to man, we find the figure is in the hundreds of thousands. And, to repeat, each of these genes stands for a basic servo-mechanism. Yet, at the same time, within the limits of a physiognomy which expresses each given function, there is in each gene also a certain degree of indefiniteness, each of which expresses shades of difference in the working out, whence all the points which distinguish one individual from another.

Apart from the fact that the various genes carry the quantity of information necessary for direction of the whole constructional programme of an entity as complex as a human being, the superabundance of the potential information which they embody is such that the number of variations which may be allowed in the structure of a gene responsible for any function is to all intents infinite. After all, we do know that little by little these genes have changed their aspect in the course of the evolution of a species and that distinctions of detail may always be expected between any one individual and another.

This very general observation we have already had occasion to make. We developed this idea when we were speaking of the possibility of a " formula " for living matter and endeavouring to show that the moment we envisage a protein containing a number of amino-acids, the number of feasible configurations of this exceeds that of the atoms which would be contained in as many universes as there are atoms in this one. This amounts to saying that within the framework of any precise given general physiognomy there is the feasibility of countless variations. For the prodigious quantity of information contained in the genes stands for the whole history of the species. It therefore includes countless details which man has so far not learned to read at all.

We thus have here the material for a new and stupendous *science of life*. I never tire of repeating that one of the great tasks of tomorrow will be the reconstitution of the past. It is feasible now to do this by proper analysis of all the traces which that past has left all round us. It is merely up to us to learn to read them. In recent years we have acquired remarkable techniques, such as carbon-14 dating, isotopic analysis of the atoms present in a given substance, or tree dating. Together these techniques have already made it possible to write the broad lines of the history of our earth. When we come to living creatures, their

history proves to be in their genes, which as their self-reproducing agencies must contain a mass of information. We have good reason to ask whether, some day, as a result of systematic examination of the genes of any creature, it may not be possible to reconstitute the life of its ancestors.

Yes, you ask, but what concrete form does all that information take? What indeed is the actual set-up of the gene? Here again we come upon surprises.

As we know, our nucleoprotein is formed by the combination of a protein, in other words, a chain of amino-acids, and DNA, deoxyribonucleic acid, together, as rigorous examination shows, with a very minute quantity of yet another substance, RNA, ribonucleic acid. We have already noted that this deoxyribonucleic acid is a chain structure, with sugars and phosphates alternating—in theory, it would seem, *ad infinitum.*

Well, complete analysis finally gives us precise information about two further features of this scheme. First, we find that the gene contains not one deoxyribonucleic acid chain, but two, helically arranged. Secondly, the sugars in the chains are united to bases which are of mainly four types. Their names are adenine, thymine, guanine and cytosine.* These four substances are of first-class importance in matters of heredity, that is to say, in the programming of any living creature. For all the programmes of all the living creatures can be written with these four symbols! If we designate them as A,T, G and C, the way in which these four letters are distributed about the chromosome chain, their sequences, their topology, the number of them present and their order, furnish us with the most varied forms of life. It is one of the great tasks lying before genetics to teach us the meaning of all the combinations conceivable from these four factors.

This is not all. I refer above to the existence of two chains of deoxyribonucleic acid, and remark that either can possess combined bases. Now, it is these bases which ensure union between the two chains. But that union can only be made in one definite way. For instance, adenine will only join on to thymine, guanine

* Of course, there are more substances than adenine, thymine, guanine and cytosine involved in these complex chemical processes. For instance, the Fiesers also indicate the base uracil. The importance of the four principal ones does, however, seem beyond dispute.

will only join cytosine. The significance of this is that one chain conditions the other. And this at once suggests the phenomenon of mitosis, or cell division, for when we have such a double ribbon, either chain forming it is able to reconstitute the other half from the elements available in its environment.

We may picture the double chain like a rope ladder.* (See Fig. 7. Also see Plate III.) Our ribbon of deoxyribonucleic acid, consisting of twin chains, with cross-links of two kinds, is like such a ladder made with two different sorts of rungs and also twisted helically. The rungs of one sort have their own special sockets, adenine and thymine. Those of the other sort also have their own special sockets, guanine and cytosine. In short, AT rungs and GC rungs. And these two symbols are capable of writing the whole history of life!

This, indeed, is another great discovery. The history of life is written in what mathematicians call binary language.

Where else have we recently heard of binary language? In the theory of automatic machines! † The non-specialist reader may acquire a first glimpse of what such a language implies from the Morse alphabet. In this, every letter is reduced to a combination of two symbols only, dots and dashes. For all purposes in which all questions are simple ones, requiring one of two answers only, *yes* or *no*, such a system is the most logical of all.‡ To translate any matter which is complex into such a language, one merely needs to break it down into a series of stages of *yes-or-no* questions and answers.

Exactly like this perfectly logical binary language, our sequence of AT and GC in the genetic ribbon offers us a very rich language, because in it all combinations are possible. Further, no matter

* In *Discovery* for January 1954 there was a fascinating detailed account of the development of the picture of DNA as a helical ladder linked by two types of rung by Dr. F. H. C. Crick, to whose work, together with Dr. J. D. Watson, as part of the Medical Research Council unit's research in the Cavendish Laboratory, Cambridge, we owe the first description of DNA structure, and as this account is a model of lucid presentation of the most abstruse scientific work, it is well worth studying by any reader whom this fascinating revelation interests.

† Cf. the author's work: *The Age of Robots* (*L'Ere des Robots*).

‡ Binary language: a mathematician's term for a system of calculation based on two numbers only. Our present system is based on ten. Systems based on twelve and on other foundations have been known. The "yes-or-no" nature of binary language makes it highly suitable for use in some electronic computers.

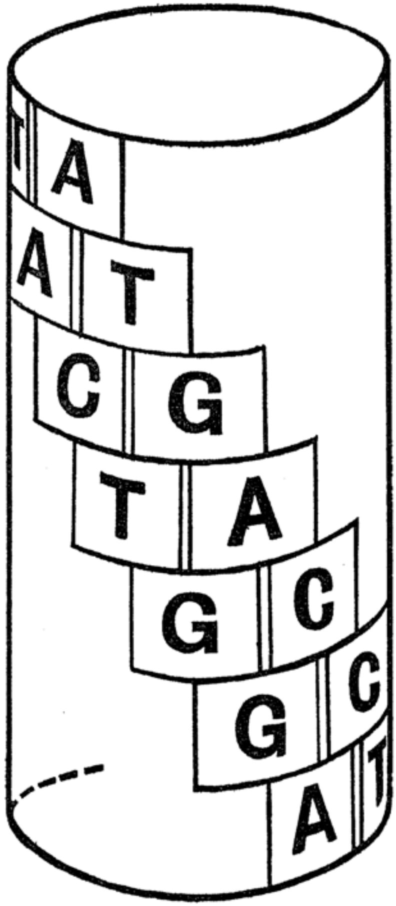


FIG. 7. A REPRESENTATION OF DNA STRUCTURE

A much simplified diagrammatic representation of the way in which one chain of the DNA helical molecule is linked to the other.

what sequence of the symbols we have (that is, which compose the sequence and in what order), every statement means something. I have elsewhere emphasised the value to us of such a system. It is supremely economical in its use of information. It is also totally free from the irrationality of all our human "universal languages". After all, they all need anything from twenty-six to thirty-four letters. Further, a haphazard sequence of them almost never means anything at all.

The fascinating problem now is to make out how we get from this binary language of the genetic ribbon, with its indications all coded in two symbols only, to the living creature. Indeed, how does a binary sequence enable the construction of the basic proteins, that is, of these amino-acid chains which, together with nucleic acid, give the programme of the living entity?

We have, as I say, two types of rung. But since the chains (the "rope ladders") are twisted helically, starting from any given point we find the rungs taking on not two, but four forms, namely AT, TA, CG and GC. Let us now suppose an amino-acid attached to each link, the nature of this being determined by the actual rung and also by the rungs on either side of it. Such considerations fit in with our knowledge of the length of an amino-acid—the distance between two rungs. They merely imply that a triplet of rungs would control some specific amino-acid. This is quite likely.

It is a simple calculation that taking three out of a total of four elements offers us twenty possible combinations. We therefore merely need to admit that the nucleoprotein embraces twenty types of amino-acid (and experimental work seems to confirm that, though there are theoretically twenty-seven amino-acids, we do not meet them all in one protein, but as a rule only seventeen or eighteen), to see that this key system of translation lies at the basis of a tremendous hierarchy. The fact is, at the top we have the binary language of the AC and GC rungs, these coding the programme of the living entity and allowing for the construction of proteins utilising twenty types of amino-acids, these in turn giving rise to cascades of enzymes, these in turn being responsible for the substance and the structure of the various organs, for all the functions, for the character and for the movements of the living entity. . . .

THE "HOW" OF EVOLUTION

We can now examine the machinery by which, utilising the data contained in the genes, nature behaves like a real computing laboratory concerned with the continued improvement of the species on the lines of systematic increase in the servo-mechanistic power of the living entity.

Not that this little word "calculations" should deceive us. I

say deliberately, behaves *like* a computing laboratory. For these "calculations" have nothing to do with any kind of thought. What we have is merely experimental mathematics—trial-and-error mathematics. Making use of the genes as spokesmen, and giving instructions for the construction of a living creature, with such-and-such features, nature in fact has no other course but to ensure that the features take account of those of all-preceding creatures which survived. That is to say, those ancestors which were the best adapted for life are carefully considered, and one sticks to the term *calculation* to describe what happens because we have here a process by which the species tend to evolve in the direction of those features which proved the more advantageous.

We may be surprised that such trial-and-error mathematics should bring about the formulation of programmes as precise and as perfect as those, for instance, of the organs in our own bodies. Nevertheless, this is certainly the fact we need to bear in mind when we bring out the two very different ways in which the answer to the problem can be calculated.

Let us take an illustration, the concrete case of a manufacturer of metal cans. He is anxious to give his cans such proportions that the loss of raw material is minimal. For instance, stamping circular bottoms out of a sheet of tinplate, he loses all the star-shaped pieces of metal between the rows of tangential circles. He wants to find the relation of diameter of can to height which will waste the least material.

There are two utterly different ways of calculating the answer. The mathematician may work at his equations till he establishes the ratio: the cans should be 1·103 times as high as their diameter.* The calculation takes only half a sheet of paper and could be of great practical use to an engineer.

But suppose we have a chain of factories which just have not got a mathematician! What are they to do? They will work by chance. Or, rather, by trial-and-error. They will stamp out a series of cans with height equal to diameter, others with height equal to one and a half times the diameter, yet others with height twice the diameter, and so on. Clearly the factories at the wrong end of this series will go out of business, because they will use

* This odd coefficient $= \frac{2\sqrt{3}}{\pi}$

up far too much raw material. There would thus arise a gradual process of natural selection, till none was left which adopted standards very far from the ideal formula, and in the end that factory triumphs which by chance hits on the proper value.

This extreme method, however, does not interest our living species. There is indeed a more subtle method. This is to take arbitrarily the mean of two values considered to be good. If a second chain of factories springs up stamping can bottoms based on the mean of the values adopted in any two factories of the first stage of trials, statistical calculation will tell us that the scatter about the ideal value will have been greatly reduced. When next this method is repeated, the error will be still further reduced.

THE GREAT STEP FORWARD: SEX

But let us get back to our history of life. There are *a priori* two solutions for the reproduction of the living creature. One is caryokinesis or mitosis, the system by which the cell entity becomes two cells by division. One individual gives birth to two, each of which is a replica of the initial one. With this system, the living entity is immortal, able indefinitely to continue its experiments, continuously accumulating fresh tuition by which it guides its evolution. The other way is by sexed reproduction, where two entities taken by chance from among living creatures pool their hereditary patrimony, to give birth to a new individual which in a sense is the " average " of its parents.

Now, this second solution is infinitely preferable for rapidity of advancement. For the events which affect a species may to a certain extent be compared to the series of readings of a magnitude made by a physicist, who is never able to calculate the exact size of the magnitude, because a number of fortuitous factors always intervene producing an element of " error ".

Now, to reduce the error in such a case, the standard solution is precisely to make as many experiments as possible, then to " take the average ". It is easily demonstrable that as the number of trials increases, the error decreases.

However, this leaves us with the following question. Suppose we can only make ten readings altogether, which solution will give us the smallest error, the average of ten trials made by the

same physicist, or the average of the averages obtained by two physicists who have each made five trials?

The answer is quite categorical. It is the second method which is the better of the two, for the result it gives is at least no worse than that of the single group of ten trials, *and it may be better.* If we suppose our two physicists to be two practically identical people (identical twins, let us say), and that they work at the same time and under identical conditions, it would then be all the same whether we made use of the services of only one, or of both. But granted a difference between the two investigators, the dual system is the more favourable one. The greater the difference between the conditions, the more this is the case.

This result is in probability mathematics well known as the " substitution of two groups of trials for one ". In statistics it has important repercussions. It is certainly of capital importance in the vast statistical calculation which constitutes the history of evolution.

Let us suppose two lines deriving from the same ancestor. The first line reproduces by mitosis, the second sexually, the new being adopting the " average " of its two parents' qualities. With every generation the second of these two lines will show a certain gain over the first, and this gain will increase as time goes on. This amounts to the statement that in the first line evolution is slow. Hence, given both systems, by the simple application of natural selection, the second will in time eliminate the first.

Thus we see that in the history of life reproduction by sex must have originated the moment it was feasible, and that moment was provided by the structure of the gene. Here let us also note a consequence of the observation made above: progress has all the more chances of being rapid if the conjugation of the two sexes involves individuals produced under increasingly differing conditions. This meets the classical insistence on the advantage of unions which are not between consanguineous parties. There is a further corollary to be drawn: other conditions being equal, evolution has been the more rapid where it has been able to take advantage of the greatest number of creatures. This condition was best provided by the spaces of the Old World.

Today, heredity studies are overshadowed by the name of Mendel, whose work provided a formulation of the laws of

heredity. So far, however, heredity has been dominated by the qualitative aspect. It will now be interesting to press this science further by subjecting the governing factors of heredity to a quantitative appreciation.

Let us start with the simplest possible case, one frankly theoretical, that of a creature which involves only one single gene. After all, everybody knows that creatures are possible in which one gene (or one group of genes) seems to act quite independently. The classical example is the Minorca domestic hen. There are two breeds of this, one black, the other white. We might as well take these two possibilities, the white and the black, to stand for our fictitious single gene.

In reproduction by sex, the chromosomes of both parents are duplicated. A series from one parent join with a series from the other. In the given case, we may represent the white parent by the symbol W–W, the black one by the symbol B–B. Crossing the two races will give the only possible combination: W–B. We experiment. We cross a black cock with a white hen (or *vice versa*). We get speckled chicks. The argument after this is easy to pursue. Crossing two of the brood, whose formulae will be W–B and W′–B′, we shall get four new combinations, W–W′, W–B′. B–W′ and B–B′. There will be one white chick, one black, and two speckled. This is the standard result. It is exemplified in various ways. All make the point that heredity can "jump a generation", so that "self-coloured" creatures reappear in the second generation. The discussion clearly boils down to the analysis of combinations, and it is for the mathematician, using Newton's binomial coefficients, to find out the relative proportions of all possible crossings at the end of any number of generations.

However, over and above these elementary considerations, there is a quantitative aspect of the problem which is not without its interest. Instead of taking colour, which offers us two basic states, let us now preferably take a coefficient which determines the shape of an organ. Let us take the case—again quite theoretical, of course—of a gene responsible for transmission of such a coefficient. In one random crossing we shall *a priori* find all possible groupings. If we represent the various animals by such symbols as 10–4, 8–6, 2–5, 7–7, the crossing of a 10–4 and an 8–6 thus gives rise to a 10–8, a 10–6, a 4–8 and a 4–6.

Now let us suppose that the ideal value of the functional coefficient of the organ under consideration (putting it in a form in which the mathematician can handle it in his equations) is 6. Let it now be understood that though at the outset nature is ignorant of this value (or quality), those animals which possess it (or in which the coefficient concerned has a value approximating sufficiently to this value) are favoured and tend to survive. Take the averages of the figures supplied by the parents. We see that the 4–8 specimen in the preceding example will survive, whereas the 10–8 (whose organ is characterised by the coefficient $\frac{10 + 8}{2} = 9$), will be less well adapted and in all probability doomed to disappear.

Of course, in practice there will be no question of suggesting that a gene embodies merely one coefficient. We have, on the contrary, made a point of emphasising the fantastic amount of information which any single gene contains. It is bound to appear, not as a number, but as a great collection of numbers. This, however, does not in the least affect our argument. It merely reminds us that the gene may be represented by a mathematical scheme, that is to say, by a table embracing a large number of coefficients. This table is affected by the whole history of the creature. In reproduction by sex we see a process by which the combination of two half-chromosomes, derived from two parents, provides the animal with a programme in which all the indications are *the means* of those in the corresponding programmes of the parents.

We can therefore say that the living person "assumes the average" of his parents (a fairly definite consideration regarding some characters, such as longevity) or we can put it rather differently and say that he ensures a combination of the separate programmes which his parents offer him. We may compare the conjugation of two sets of half-chromosomes with the way in which today the chemist makes plastics by making two chains of the same elements (as a rule two monomers) react together when arranged in different orders, the order being here a code responsible for the eventual characteristics of the substance. Here, the product obtained from two initial chains, A and B, may emulate the characteristics of either A and B, without the defects of either

or with those of both. These considerations have assumed great importance in the modern chemical industry. For instance, we know that polyvinyl chloride is ideal for water-pipes, to replace those of copper or lead. But unfortunately it softens* seriously from 60° C. Hence research is now directed into the discovery of a monomer which will remain solid at over 100° C., the boiling-point of water.

In the course of evolution we need to distinguish between two processes. On the one hand, in virtue of the action of the soma on the germ explained above, environmental variation changes prompt a systematic " shift " of all programmes in a definite direction. Thus, for instance, we see the height of animals increase when they dispose of abundant food, an observation which, as recent statistics seem to have proved, refers to the human species too. We also know that in the long run when, by the principle to which frequent reference has been made, new servo-cycles develop, such a shift of the programme of a living creature may result in the appearance of new functions.

On the other hand, supposing the outer environment to remain strictly unchanged, we find the species evolving slowly because of the programme conjugation which now takes place among the genes. This sort of evolution results in bringing the various organs of the individual towards the formula which is ideal for the accomplishment of their work. Each organ is thus gradually " tuned up ", after countless experiments to assume the adequate form, the precision of which today amazes us.

The machinery of natural selection, which allows the best-suited individuals to exist, may further be compared to the procedure which the physicist utilises today to separate the isotopes of an element, for instance, in the very well-known example of manufacture of " heavy water ". One part in about 5,000 of water is formed not by a combination of oxygen and hydrogen, but a combination of oxygen and *deuterium*, or " heavy hydrogen ". The principle used to obtain a quantity of this " heavy water " is to separate out the heavy molecules. Now, since the deuterium oxide (" heavy water ") possesses a greater inertia, when ordinary

* It begins to soften noticeably at much lower temperatures, as those who use it in garden hoses will have noticed, but from 60° C. upwards it ceases to be usable as water pipe at all.

water (containing $\frac{1}{5000}$ parts of " heavy water ") is electrolysed, the residue inevitably contains a higher proportion of heavy water. This process is repeated, and the residue contains more and more heavy water, till after the seventh stage the residue contains 99 per cent. " heavy water ". In like fashion, every living species has been enriched by individuals whose organs were better adapted, providing the individual with greater opportunity of using his servo-mechanisms to survive. It is the enormous number of actual trials that are made which explains the amazing precision of the results which life has been able to attain solely by means of its natural experimental mathematics.

MUTATIONS

It should now be clear how the gene-programme principle utilises the phenomena of mutation to which such great importance is accorded today.

With the construction programme of a living creature recorded as it is on the nucleic ribbon by the remarkable coding system provided by the two fundamental rungs, it seems that the simplest and surest way of radically changing the structure of any animal or plant is to produce changes in the ribbon. Is there any hope of being able deliberately to change all the characteristics of the living entity by shuffling the order of the basic parts on the ribbon?

Such changes certainly do sometimes take place accidentally, as a result of the radiation to which the genes are subjected, or by reason of faults of reproduction during the manipulation of the chromosome ribbons. In this way spontaneous mutations appear. The creature constructed on a programme thus altered must *a priori* possess different characteristics. If the multiplication of their progeny is ensured, they may well originate a numerous race.

This machinery has given rise to some fascinating cases. In 1791, in the United States of America, a freak lamb was born on a farm. By this sort of spontaneous mutation, it had a long body and extremely short legs. This seemed most valuable to stock-breeders, because though the animal yielded as much meat or wool as any other, it was unable to jump fences, hence easy to handle.

For this reason the freak was carefully looked after and its multiplication was encouraged. The ancon or " otter " breed of sheep resulted. It lasted for a century, then died out, though it appears that another lamb with this characteristic appeared in Norway in 1949.

Apart from such natural mutations, which happen to be very rare, the principle of artificially inducing mutations by means of X- or gamma-rays has been employed. By subjecting an animal's genes to such radiation, the gene structure can be radically changed, to provoke all manner of changes. The number of mutations obtained is always proportionate to the radiation dose, becoming very frequent with high intensities. Thus, with a dose of several thousand Röntgens the proportion of *Drosophila* flies with mutations can be stepped up to one in ten.

This deliberate bombardment, however, still results only in " chance " mutations. The balance of the experiments in artificial mutation which have been made in recent years is instructive. We have obtained freak mice and wingless flies. We have also acquired useful new varieties of plants, giving greater yields, the most outstanding being an atomic " super-maize ".

This clearly shows that the possibility of improving species by artificial mutation constitutes a problem, and a two-faced one, too.

In the first place, with our present techniques, by which we can only produce haphazard mutations, the work is the same as if, for instance, one blindly switched the values of condensers or resistances about in a radio set, or snipped at random through this or that circuit, to see the result. The chances are very high that no good would come of it. The vast majority of the haphazard " mutations " thus produced would be of no use to us at all. Nevertheless, in our radio set certain changes which resulted might prove to have a one-sided result. For instance, one might chance to increase the power of the set, but at cost of musical tone. This, for instance, would definitely result if our random snipping of circuits cut out the condenser which shunts the loud-speaker. Or, accidentally cutting out the set's selectivity circuits, one might succeed in receiving a single local station very much better. And so on.

Thus there can be random mutations which turn out to be useful. We have mentioned above the case of those short-legged

sheep and the prolific maize. But such results should not be allowed to delude us. Acting on the gene in this chance way, one cannot fail to diminish the total quantity of information it contains.* Therefore the total servo-mechanistic power of the creature we thus treat will be diminished. Though we may get improvement in one single respect, we must not lose sight of the fact that we are at the same time seriously handicapping essential biological processes. The creatures affected by the mutation will all round be inferior creatures and they will be bound to disappear by the working of natural selection. True, we can mask this effect by our intervention. After all, these freaks which we have considered do not live in the wild, but under conditions controlled by ourselves. This being so, we can look to man to supply the servo-mechanisms which these new eccentrically specialised creatures now lack.

This is a very important law indeed, one of which our civilisation will some day be obliged to take full account. Since biological machines are planned to perpetuate themselves automatically by reason of the organisation which they themselves possess, when that organisation is changed their autonomy vanishes. This means that man must be very cautious about any attempt to suppress what biological processes have developed, for that suppression demands a new kind of control and permanent intervention by man might well prove a crushing burden.

This is true for both the animal and the vegetable worlds. It is also true of man himself. So far he has made only spasmodic clumsy use of the benefits of civilisation. But now, obviously, his dream is to achieve the full benefits of the reign of artificial devices, to relieve himself of all those efforts for which, after all, his organism was conceived. . . .

But let us return to our problem of mutations. We have remarked that a haphazard modification of the genes must *a priori* diminish the creature. Everything would, however, be

* As this book goes to press, fascinating reports appear of the work of Prof. J. Benoit, who, by injecting a serum derived from one kind of duck into the eggs of another, has upset the original nucleic ribbon in favour of certain characteristics of another pattern. What is still more interesting, is that this chemical re-shaping of the programme in the initial stage of growth has proved a hereditable characteristic. Parallel effects have been obtained by blood transfusion at the Moscow Institute of Genetics.

very different if we could make use of another method of procedure—if we could work, conscious of what we were doing, if, indeed, we really did succeed in changing the gene precisely as we wanted. That will be possible only if we now find out the correlation between the structure of the gene and the characteristics of the living creature. This achieved, it is obvious that careful modification of the gene could without harming the total programme well improve the creature in any desired sense, just as, for instance, today the services of plastic surgery can not only save life but also have an aesthetic use.

This stripping down of the genes which will be essential for the knowledge we need constitutes a terrifying task. No part of it has so far been achieved. The most we have been able to do is to map out certain possibilities regarding the little *Drosophila* fly (which we use because it multiplies so rapidly and is so easy to handle). But we still have not touched on the chemical problem.* In my view, this work will be impossible until we have improved the mathematical tools we need, and also secured the aid of electronic computers. Electronic computers indeed we now have. Therefore it would seem that the task indicated constitutes one of the most entrancing vocations of the science of tomorrow. Were it to be accomplished, it would be possible for us to do whatever we wanted with all the forms of life.

* See footnote to previous page.

CHAPTER VII

The Fundamental Acquisitions of Life

STARTING from the hypothesis of an initial earth offering a fluid environment of known composition, we have so far deliberately based all our argument on logic. Without dwelling too closely on the variety of forms of life which our world offers us, I have for my part been at pains to show how life could appear automatically and further evolve automatically.

What we have to do now is glance at what this machinery actually produced. And there we come upon our very first question. If everything in this development was logical, why did not one single type of life develop? Why was there not one single formula to give one form of living creature of steadily increasing perfection?

I rather think the answer to this has already been given. It was given when the initial tendency of deoxyribonucleic acid to associate with protein, to enable it to combat the principal factor in variation, was pointed out. But this factor has never been a constant. It has incessantly changed from one point to another. This means that we have to look to the very start of life for the origin of our differentiations. Later, living things were situated in even more varied conditions. Here the environment was a tranquil cave in which the temperature of the sea varied but slightly. There, it was a channel washed by powerful currents and subjected to considerable temperature fluctuation. Apart from this, the basic climate of the earth varied too, according to latitude, to seasons, and to the geological period. Variations in climate were indeed most important. For instance, the life of a forest is largely conditioned by its first years of life. We must also bear in mind that the amount of light received in the primitive waters of the earth varied with the depth, not merely in intensity, but also in spectral composition, the various radiations being unequally

absorbed at various depths. And above all we have to take account of the natural action of the various forms of life themselves.

For, the moment that any dissymmetry showed in the world of life, the set of differentiations could not fail to accentuate with each successive stage of evolution. Thereby, the problems to be solved to ensure self-reproduction became different. The principal concern of life changed with the circumstances. Thereby the nature of the servo-cycles of the living creature also changed, and finally so did the shape of living things and all their features.

The history of life, indeed, might well be compared to an enormous multiple chess game in which the " rules " are very firmly laid down and are all adhered to, but the board is so big that it is impossible for all the players to have the same game in mind. In addition, at the very outset certain factors put some of the pieces out of position in a random way. Indeed, something the same keeps on happening even while the game is in progress. Life plays a game of chess against its outer environment, while from time to time external factors of which the living creature has no cognizance at all, intervene, changing some of the pieces and setting in motion various totally new games.

Thus, between any two stages of evolution, living things strive to reach some objective prescribed in a given formula. They work towards the improvement of their organs so as to attain the best embodiment of that formula, based on the programme in their genes. They evolve towards a given constitution which, provided nothing happens to upset their particular servo-cycle, it will be possible to maintain indefinitely. This amounts to a definition of " fundamental states " which are just so many " minor evolution " solutions of the great equation of life.

What, however, really interests us is the " major " evolution, by which the basic formula of living forms is modified. It is the machinery of this that we shall now follow step by step.

. . . . .

In its make-up every living creature possesses a given power of servo-control with regard to certain factors. As we have observed, putting it in another way, it struggles against chance. This way of putting it is perhaps a more convenient way of " coding " the growth of servo-mechanistic power in the living creature. This

struggle against chance can be assessed by examining the various factors in its outer environment which a living creature controls, and the extent to which that control works—that is to say, by examining within what limits the living creature can assure its own self-reproduction. For instance, a living creature is capable of struggle against the diversity of the materials which may form its food and against any possible temporary shortage of that food. An extreme case is the camel, which is able to store up water. It can also cope with environmental temperature changes, and so forth.

Schematically, once we leave the initial stage (during which a molecule is able to construct another molecule exactly like it, provided the environmental medium is of a given composition), the whole history of the progress of the living creature boils down to the problem: how to ensure that reproduction when first one, then two, then three, and eventually when *n* factors in the environment are altered. The number of such changing factors and the limits of variation in each variation together indicate the extent to which there has to be this struggle against chance. This is the machinery of evolution, and the creatures which survive are plainly those which are capable of facing up to the broadest range of external events.

Here the mathematician is tempted to suggest an engaging graphic representation. For instance, taking only two factors, we can say that the servo-mechanistic power of the living entity is expressed by a line which regarding every value of any factor indicates the variation limits of the other factor within which the entity can survive. This gives us a closed curve, which represents the " realm " of the particular organism, that is to say, its field of struggle against chance. Of course, if we take a number of animals which we suppose to be living quite independently, this graphic representation of the realm of each of them will also reveal the realm which is theirs in common. And the graph will also show which species will survive when there is violent alteration of one of the factors. (If we presuppose a slow change of a factor, we may assume the animal's adaptation to it, in an effort to extend its field of servo-control in that particular direction.)

Unquestionably, this needs qualification. Though, for the given conditions, this curve is a good indication of the realm of

survival of a creature, this must be slightly different for every member of the species. The true graphic representation would be a sort of shadow zone representing a progressive transition from the realm within which every single member of the species survived to another in which none did. To find oneself situated in the intermediate zone (meaning either a crisis of the species or war with some other species) constitutes an interesting case, since it allows us to speak of a process of acceleration of natural selection and hence of evolution, first, since all the less well-adapted individuals stand every chance of mass extermination, and further because calculation of the probability involved teaches us that it is in groups of individuals which are neither too small nor too large that the acquisitions of experience have the greatest likelihood of being established. Indeed, the history of life has taught us that it is in such cases, in which the species is threatened by an event which takes it deeper and deeper into the intermediate zone, that we see the most spectacular acquisitions.

If, however, we wish to characterise the species, we have the right to consider replacing this intermediate zone with a fictitious curve, to envisage this theoretically clearly defined surface which it marks off in two dimensions.

This case of two factors is entirely theoretical. In practice we need to generalise about any number of factors. If there are three factors, the mathematician will make use of a spatial representation. Beyond this, since we lack any concrete means of depicting a space with $3 + n$ dimensions, discussion is made possible by analysis and reference to the "hypervolumes" of that space. A serious question, however, arises: what is the total number of factors capable of interesting the living entity, or, in other terms, how many dimensions must the struggle against chance be given? The answer, of course, is that there can be no limit. In practice every single event in the world about us may offer phenomena practically unlimited in number, so that the combinations of these are also completely indeterminate.

In short, in the actual hazard of our universe, it is not even possible to assess the number of the factors which may form its dimensions, because, if for no other reason, we have no indication how many possible events this chance offers us. After all, if we had, it would by definition not be complete chance. In other

words, we have to take account of a notion infinitely more generalised than that which the mathematician makes use of, since as a rule he limits himself to consideration of mere " linear " chance, in the form of the random values which may be assumed by one given variable.* When he does this he is admitting only one-dimensional chance and dealing with only a special problem.

Now, over and above all this the element of chance against which living things have to struggle does not consist solely of the value of certain factors. These factors also have their nature, and their number. It is all these aspects together that form the whole randomness of things. This is a real chaos from which, for that matter, at first nothing precise emerged, neither time, nor temperature, nor pressure, nor differentiated substance. All these factors appeared by reason of the play of various organisations of matter and physical servo-mechanisms, but without any final count ever being considered, for the interaction of the events of the universe is capable of giving rise to the most varied of factors.

Thus, according to place, period and momentary conditions, the living being is bound to see the world about him change as a function of a multiplicity of factors. Consequently, the living entity must exert its powers of servo-mechanism in a variety of directions at once. Whence of course the great number of differentiations. They are manifestations of the incredible variety of existing species, each, by the fact of its own history, having a well-marked " domain ".

Even under the hypothesis of the physical conditions remaining unchanged, it is impossible to indicate any intrinsically limited chance, for the mere proliferation of creatures, whether of different or of the same species, in any area, and the fact that they " interfere " one with another, by fighting for the same food, or by being

* A word of explanation may here assist the non-mathematical mind: Where only one factor in a situation varies, the line of development is called " linear". Where more than one factor varies, and one may vary against another, the description of the development in mathematical terms is not " linear ", but multi-dimensional. When more than three factors are involved, the mathematics may involve a geometrical approach which involves a fourth dimension or even more than four dimensions. This has nothing whatever to do with space-time problems or spirituality, as some imagine, but is merely a way of picturing complex developments in order to discuss them satisfactorily. That is what the author refers to four paragraphs lower when he speaks of " n " (i.e., an indefinite number of) dimensions.

prey one to another, all together introduces just so many more factors modifying the environment. For any given living creature the appearance or the disappearance of another is bound to be one of the dimensions of its individual chance. Thus we have to take account of a system of interdependence and interaction which is of astonishing complexity.

One observation, however, will interest the mathematically minded. One can theoretically define the realm of existence of any living creature as a space with n dimensions. Now, it would seem that n is infinity. The case, however, has been studied. Here I principally have in mind Frèchet's entertaining work on abstract spaces. After dealing with spaces with a given number, or with given types of dimensions, Frèchet turned to spaces with an infinite number of dimensions. He went into the matter very thoroughly indeed, taking spaces which all had the same infinite number of dimensions, then the effect of adding types of dimensions, and so on and so forth. In my view this mathematical work offers us an instrument which will eventually enable us to study the struggle against all forms of chance in a systematic fashion.

To return to our story, what meanwhile has become of the history of life? Through a cascade of successive differentiations, this appears now as a series of struggles, each aimed at the mastering of some hindering factor, in the way which experiment shows to be the most advantageous. This brings us to considering a transformation of the living creature on definite lines which are suggested by the circumstances, yet perhaps are not intrinsically the best. But when a function depends on more than one variable, it is often feasible to increase its power by acting on any one of a number of the variables. It is one of these variables that is indeed chosen by life for alteration, the living creature incorporating this new feature in its cycle of servo-mechanisms.

Nothing, however, proves that this variable was therefore necessarily the one which the mathematician, with his study of the whole of the problem, would have selected to work on. Changing this particular variable, one can indeed effect an improvement of the given servo-power. But only for a very short time. After that, one reaches a stage beyond which no further improvement is possible. There is then an impasse. For there can be no question of going back. The matter integrated in the cycle is no longer

available. One cannot undo the cycle now built into the creature's basic programme.

Here one may suggest comparison with a settler starting out from the summit of a mountain, to reach the lowlands and find more clement conditions. His general decision of course is to " keep on downhill ". If, however, he does so blindly, he may be like a rock tumbling haphazard down the mountainside, which selects the path which at any moment is immediately the steepest, although this may soon lead to a crevasse surrounded by a rocky wall, in which it is imprisoned, unable to escape again. In such case, the would-be emigrant perishes high up on the mountainside, while all the time there were other paths which would have taken him all the way down to the snug city below him.

In this way, the world of living things is a veritable hail of rocks tumbling pell-mell downhill. Very many of them get trapped in blind alleys. It is only after a whole series of variants that one can at last speak of a solution advantageous enough, one which provides an increase in the servo-power, one achieved by adopting yet another path which happens to be the right one—one which does not trap the animal and prevent further evolution.

Now, each time the path before it forks, that is, each time it is faced with two possible solutions, why does the living thing not rationally choose the advantageous path? Precisely because in these matters we cannot consider the living creature biologically to be a reasoning, rational thing at all. It has no awareness whatsoever of the changes in question, let alone of any future of its kind. At any given point it evolves along the path which seems at that stage to be advantageous. It has no greater power of choice than this. It submits to an ineluctable process.

Here indeed is the danger of all specialisation. Whenever the whole of a species takes a certain specialised path, it stands self-condemned to know only the ways-out offered by that particular specialisation. Thereby it cuts itself off from any improvement, however feasible this might otherwise have been in any other direction.

Reverting for a moment to our picture of the " domain " of every animal, we see that whereas we can represent all-round ability by a spherical domain, that of the specialised creature must be depicted as an elongated domain, its long axis placed along the

line of specialisation which it has selected on the potential sphere. We find such a creature is astonishingly vulnerable when attacked from some other direction than that which it has "chosen". It is the story of those famous gun batteries which Great Britain installed at Singapore. The aim was to make that city a strong-point of the Far East, but the expensive cannon made it rather too limited a fortress. All the gun emplacements were too specialised. They envisaged attack from one direction, from the sea. The planners had ignored the possibility of an attack from any other part of the horizon. But that is precisely the sort of attack to which in 1942 Singapore was subjected. The Japanese swept overland through Malaya, to enter Singapore from the land side, without any real resistance being feasible!

When we contemplate the torrent of history of all living creatures, all sprung from one initial cluster of molecules, but today scattered all over the world in hundreds of thousands of vegetable and animal species, there can be no thought of writing the story of them all. In any case, there would be no more point in such a labour than in a detailed report on a million games of chess. The important thing for the chess player is to know the rules of the game and the leading games which have been played.

As far as these go, there is another point to notice. There is quite often a convergence. Species which are quite different one from another, making for the same target have identical reactions. They solve problems in similar ways. We can point to structural evolution resulting in the organisation of an internal environment —the internal organs—which is astonishingly alike in animal and plant. For instance, plants make use of methods just like those of animals to protect their seed. Spores give place to seeds constructed in the heart of the plant. The mammal, which used to eject its young from the parent body in egg form, first provides an intermediate stage in the form of the marsupial pouch, then produces the *placenta*. We find a similar convergence in the development of internal organs. The *solidary* gland which we find in the digestive tube of shellfish and crustaceans is the analogue of the vertebrate's liver. There is further convergence in the organs with which very different creatures tackle the same problem of picking things up.

In short, over and above all the many changes in living

conditions which are imposed by local conditions, the general living programme of systematic increase of servo-powers forces on a variety of creatures general lines of development which dominate the whole history of living things. Altogether, they amount to so many basic acquisitions which have their proper place in the framework of a logical evolution towards a perfect anatomical formula.

It is these generalised acquisitions which we now intend to discuss, examining rapidly the power of autonomous displacement, the birth of the metazoa, the organisation of the internal environment and the formation of the nervous system.

I. AUTONOMOUS DISPLACEMENT

Very early in the history of life an important differentiation gave rise to two worlds which in one important respect are basically different. These are the worlds of animal and vegetable life.

To understand the sense of this differentiation, let us return to the conditions of the primitive earth, when the first amino-acids had been synthesised from the constituents of the fluid environment. The first living creatures were born centred on nucleoproteins. They were the basis of further systematic syntheses. The development from virus to bacterium then took place, and there was begun that development of a natural play of servomechanisms which drew matter into the more and more effective cycles which we have already examined.

Now, at this point, what may be termed the " standard " line was to achieve improvement of the procedure by which, given carbon dioxide, water and ammonia, the creature could best utilise solar energy. To this end, an important step in evolution took place, ending in the amazing machinery of the vegetable world's chlorophyll action—the machinery by which today plants take water-vapour and carbon dioxide out of the air, while their roots draw nitrogenous products from the soil.

In itself, this machinery was the fruit of a very long and very complex evolution. Indeed, at the outset, before chlorophyll was developed, the vegetable creature achieved only a very rudimentary form of photosynthesis and absorbed only about one photon of solar radiation for every molecule of carbon dioxide. We can still

find examples of this low-level process in certain plants which have remained very primitive.

Early photosynthesis was poor, but evolution brought about a slow improvement of this process, till with the " invention " of chlorophyll the plant was able at last to step up its utilisation of sunlight to four photons per molecule of carbon dioxide utilised. This was, however, only achieved at the cost of a series of operations of startling complexity. It is only recently that, thanks to chromatographic analysis, we have even begun to understand what happened. Using radio-active tracers, we have further now discovered that in this the basic part is played by certain phosphorus compounds.

In addition to this improvement, plants also sought to acquire the maximum amount of power by increasing (as far as mechanical conditions allowed) their receiving surface. This explains much of plant morphology, in particular the appearance of large leaves, devices which enable the chlorophyll to work over large areas. Nevertheless, the vegetable world was still limited to the energy obtainable from the sun, and even when the sun was at its highest point in the sky could only bank on a power of 2 h.p. per square metre. When due account is taken of inevitable losses in the transformation of that energy, and allowance is made for other corrections which we have to make, to arrive at an average figure applying throughout the year in intermediate latitudes we have left only about one-twentieth part of this maximum!

Admittedly, when we examine a forest, the power taken makes a tremendous total. But the amount of this which reaches the individual plant remains very, very small. For the sake of comparison, we may observe that if it had to take all its energy from the sun, a plant as tall as a man could hardly count on more than a power of the order of 0·01 h.p. From *his* nutrients man draws ten times that amount!

Now, we come to the points about the two worlds. At the dawn of life, by a completely different line of evolution from that of plants, the first animals made a tremendous leap ahead. Instead of manufacturing their own organic products, they " elected " to gather them ready made from their environment.

The transition is very understandable. We need merely imagine the situation. There was a tremendous proliferation of

plant cells in a comparatively closed area (or volume), a proliferation so great that the cells were at last all touching and even beginning to layer, to form a carpet of a certain thickness. We can picture this taking place in some sheltered backwater. Under such conditions, it was only a logical consequence for some cells to start incorporating the organic matter synthesised by neighbouring cells into their own cycles, till at last the resulting lack of balance led to a modification of the servo-cycles in such a way that the cells which had experimented in this new way of life developed the regular habit of eating up other cells. It was after all a much more advantageous way of feeding, because by expenditure of the same effort they acquired so very much more concentrated energy.

However, this formula only worked so long as the cell which had thus chosen what was really animal behaviour had within reach other cells to serve as its victims. This was a new problem. In some instances, the solution found was that of the fungi, which established themselves where there was an extensive organic environment. Mushrooms are completely devoid of chlorophyll. They live either on the fermentation of decaying organic matter, or, as direct parasites, on the living tissue of plants. They were certainly to undergo a very great extension, since today we number about 40,000 species, some of which are strangely like animals, such as those soft fungi which live in masses, those we call the *myxomycaeta*, the cells of which are definitely like amoebas. They eat the microbes they come upon before joining together to form haploids.*

However, the existence of such privileged environments is exceptional. We have to ask what happened in general when cells which had got into the habit of absorbing ready-made food found themselves deprived of it? Yes, what did take place when the animal cell found itself isolated? Obviously, it had to choose between death—and locomotion.

We have above analysed the machinery of movement, and seen that this is due to changes in cell shape caused by chemical changes dictated by an enzyme. Hence we can speak of movement being directed by a servo-mechanism. At the outset, one need hardly insist, our protozoon has no notion of locomotion. All that can have

* A form of primitive plant life in which differentiation of root, stem, leaf, etc., has not yet taken place; also known as slime fungi and "mycetozoa".

happened is that experience showed that the production of certain enzymes (those which provoked locomotion) was advantageous. We had come to much this sort of conclusion in the preceding chapter. Not merely do the protista not know they are moving. All that happens is that they come to stir their bodies about, and when they do this, they are able to explore a much greater volume of liquid medium than when still, and this increases their chances of finding the food they have now taken to imbibing. The protista do not however direct their movements. It is only much later, with the first adumbration of a nervous system, the birth of sensory receptors, hence the acquisition of points of orientation, that the animal becomes capable of *directed* locomotion, after which of course it at once begins to become capable of more and more precision in this.

With the appearance of locomotion, a tremendous adventure began—the adventure of autonomous displacement, due to give animals the possibility of action in the world which was eventually to lead to knowledge of this. Farther along in this great development were improved techniques both for holding things and for moving. But the plant world, on the other hand, was doomed to remain a world of stationary organisms.

The taking up of food by the new mobile creatures was soon ensured by a specialised orifice, the mouth, which became equipped with the required accessories and for a long time kept the characteristic shape of an elongated snout. The situation here was not changed till very late, when two limbs were developed which could do the work of taking up food instead of the mouth. This advance incidentally at the same time enormously increased the possibilities of the creature's direct action on the world about it. Instead of picking up food with its mouth, it could now do this with its paws and bring these to its mouth. This apparatus then began speedily to diminish. It lost that elongation which we call " animal ". That elongation had certainly been an obstacle to the evolutionary development of what we now know as the head, a matter to which we shall return later, when we consider the creature's general structure.

The functions of locomotion must also have been the result of a remarkable evolution. At the outset, it goes without saying, the technique was very rudimentary, with poor physical results, the

animal making use, for instance, of propulsion by reaction (as today with the medusae*) or by the cilia or flagellae with which unicellular creatures are equipped.

Next came the pseudo-feet† of the amoeba, and we have also the technique of certain primitive animals which even today merely lash the water with their tails. In the fish, with their fins, we got a more rational solution. In due course there appeared a further differentiation which was the starting-point for greater things. For there had been two principal ways of solving the fin problem, and both were adopted. The " normal " group was represented by fishes with a large fin based on an important principle, that of a number of arms articulated in parallel. We call this the normal solution because it makes the greatest possible return for this method of propulsion through water and allows fishes great speed of movement. But there was another, exceptional form, which was to have great consequences. This we find in the *crossopterygians*, which are fishes whose fins have lobes, which are much stronger. These were possibly developed by fishes which needed to get about in swampy areas, or forge a way through a dense aquatic flora. The main problem here was not to achieve great speed, but to be able to overcome the hindrances to locomotion.

Consider now what happened when certain seas dried up. Geology tells us of numerous movements of the maritime zones by which the map of the world was reshaped, and we have already remarked that the amphibious creatures must have first set foot on land because of such transformations. We can imagine the process. Our two species of fish in a sea which is drying up, soon to be reduced to swamps, these too doomed one after the other to disappear, were in very different positions. The rapid fishes with their oar-like fins proved unable to cope. Their fins could not support the weight of their bodies. These fishes were doomed to perish. Those sluggish swamp fishes, on the other hand, which had paw-like fins, could use those quite well to get along. Here we had the beginning of real legs and paws.

Nevertheless, it is nonsense to ask: " How did these creatures which used their fins to swim through the water ever come to think

* Jelly-fishes.

† Pseudo-feet, i.e., the " pseudopodia ".

of using them on dry land? " The question in fact does not arise. The fishes had no ideas at all about it. They neither conceived of sea nor of dry land. All they were capable of doing was controlling a physical activity which resulted in a certain to-and-fro motion of their fins. Consequently, placed in a new environment, though quite ignorant of being in it, they went on trying to move in the same way that they did before.

Here we have the key: the living creature is *a priori* merely able to transplant its old habits to the new situation. Either those old habits prove to be of no use in the new situation, and the creature is defeated, or, even in the new environment, they do prove to be of use. In the slime and mud and in due course on dry land too our *crossopterygians*' " fin-paws ", though certainly very poor instruments for locomotion, did at least enable the creatures to get about. Hence the *crossopterygians* were enabled to go on living. Evolution after that point must have consisted in the adaptation of those " fin-paws " to the new situation. There was of course also an incentive in the fact that the terrestrial world turned out to contain an enormous reserve of ready food.

Thus life flung itself into the conquest of the dry land, giving birth now first to the reptiles and later to the mammals. Once again, according to the various paths those first animals happened to take, many differentiations appeared. For instance, the herbivorous animals (horses and suchlike) were mainly interested in avoiding other animals. This made their problem that of how to escape quickly from those which preyed on them. On the other hand, the carnivorous animals developed their limbs for combat purposes.

Finally, there was once a first creature which learned to stand up on two of its four limbs, leaving the two others free for supplementary grasping actions. Today man's motion on two legs seems quite normal to us, but it is really no more than the end of a long, patient process of evolution. Walking indeed constitutes a mechanism which is both complex and subtle. It includes numerous balancing acts, all made possible by the continuous cooperation of all the many muscles and tendons of our legs. It is indeed significant that so far no engineer has ever really succeeded in making a walking machine, that is to say, one which is mounted on two supports, by means of which it can move about on any sort

of surface, as man does on his legs. We have in walking a nice co-ordination of movement which was not feasible at all till considerable developments had taken place in the nervous system which we have yet to consider.

Apropos of walking, we may here answer an objection which is frequently raised. Why, if it could not contrive the true wheel, did nature not invent a comparable system which would provide a better yield for energy output than walking? The reasoning behind this question is fallacious. One does not dispute that on a bicycle a man can cover a hundred miles or more in a day, whereas thirty miles will overtire him on foot. Nor does one question that this difference is due to the bicycle's furnishing a better means of utilising the muscular energy of the legs. But—a fact too often lost sight of—the argument makes use of too special a case. It assumes cycling on a smooth road. The situation becomes very different on rough land, especially in muddy, marshy country, with many hollows. There are circumstances in which neither wheels nor even caterpillar tracks are of any use. But man with his arms and legs can master hedges, ditches, sharp rises of ground, even trees and perpendicular cliff faces. How could he manage all that if he had wheels instead of legs? No, precisely what makes man such a good machine is *his lack of specialisation*, that is to say, his ability to do anything, whereas your specialised machinery, for all its fine accomplishment of special tasks (in which it can do far more than a man), is unable to cope with situations outside its specialisation. After all, do we not know what happens to highly specialised creatures?

At first thought, it might seem that the victory of the animals was inevitable. Whereas they can move at will to seek their food anywhere, plants are without any defence against the animals which, finding them, eat them. But let us observe that the animal-vegetable formula implies a balance between the two " kingdoms " which has been maintained through the whole history of life. For it is clear that if the animals consume too great a part of the vegetable world, there would not be sufficient food for them. Put more precisely, there is a law of animal-vegetable equilibrium by which, below a certain density of vegetation, the amount of energy which animals could acquire in the given locality would not be sufficient to take them to the next locality where there would be

more vegetation available as food. Unless the animals let the plants live, they themselves die too.

The early protozoa tried feeding equally on other protozoa and on protophytes. Animals began to eat both other animals and plants. But essentially the bulk of the animal world lives on the vegetable world. This in concentrated chemical form furnishes the animal world with the energy required, and this is a condition that demands the maintenance of this animal-vegetable equilibrium. Besides, is it not significant that man's systematic spreading over the face of the earth only began when, mastering agriculture, he found out not merely how to let sufficient plant life live on, but how to further the development of that plant world on which he lived?

II. THE METAZOA

Parallel to this animal-vegetable differentiation, the world of life was very soon to have to make another choice between two formulae of organisation. One way was to stick to the principle of the single cell, the other to adopt that of a " society " of cells originating from interdependence between the servo-cycles (that is generalising the principle of the association of a certain number of nucleoproteins).

In the framework of this differentiation the interdependence of the servo-cycles at the same time furnished a method of linkage which made feasible the high degree of organisation attained by the metazoa.

This choice equally affected the vegetable and the animal world. Both one and the other could either remain protista or produce complex organisms.

We look upon the metazoa as more specifically initiating the world of living creatures. The protozoa are microscopic creatures, but the new principle of cell association permitted living entities to group together billions,* then billions of billions of cells, to produce quite tall creatures, the scale of which in the end had nothing whatever in common with the molecular domain from which life had sprung. The protista never exceeded a tenth of a

* Billions, i.e., thousands of millions. In Britain the word billion is used to indicate one million millions, but in U.S.A. for 1,000 millions, the European milliard, a useful number.

millimetre (about four "thou.") in diameter, whereas that of more evolved creatures was to be measured in thousands of millimetres (in yards).

It would be an over-simplification to suggest that life began with the appearance of protista, which then gave rise to the metazoan forms. We should preferably think on the lines of living cells as such being faced with the dilemma of whether to improve separately or collectively. There was definitely a stage in which both ways were feasible. Servo-mechanisms were feasible within the framework of a mere cell, or with interchange of controls between two or more cells. Here—indeed, in all the history of evolution—we should bear in mind how the Ancient Greeks depicted Chance. They made her a goddess with opulent hair in front, but bald behind. Once one had let her pass one by, it was vain to try to turn back and make any efforts to catch up with her again. Beyond a certain stage of development of their organisation, the protista were condemned to remain isolated unicellular forms of life.

Thus protista and metazoan forms developed their various improvements along different roads. Evolution was more rapid with the former by reason of the small number of data "built into" their organisational system. In general, we should note that the more perfected a species is, the longer it takes for it to master its formula, for the reason that this requires a greater number of preliminary experiments. This observation, however, should not lead us to fail to note that there was also a tremendous labour of differentiation even in the later protista. They dedicated certain of their parts to the performance of various precise functions. They even acquired something like respiratory organs, and the simulation of muscles or sense organs.

I insist on the high degree of organisation of the protista, because in them we sometimes come upon interesting specialisations. In one it is adaptation to locomotion that is dominant. Another prefers the policy of waiting for its prey, which it snaps up thanks to a set of particularly well-developed muscular fibres. More striking still, the paramaeceum has hairs which it stretches out like real arrows and these hairs are capable of wounding any enemy which attacks. There are also stentors which, when they reach a lighted zone, first move backwards, then, pivoting round

on their posteriors, set off in another direction, while with the euglenae this reaction is triggered off by a decrease in illumination. After a thorough study of these behaviours, the famous physiologist Jennings became convinced that even on the scale of the single cell one could speak of mentality.

However, the protista were to come upon an inexorable limitation of their possibilities. This was their inability to increase their size beyond a certain point. What we must realise is that the dimensions of a cell are not capable of indefinite extension, for the reason that there has to be exchange with the environmental medium. Now, with growth, the volume of course increases by the cube of the dimension, and the cell's requirements increase in like proportion. But the surface of the creature only grows by the square of this. Hence, inevitably, with growth the profit-and-loss account of the cell's exchanges with its environment tends to get out of hand. There are indeed exceptions, such as a seaweed, which takes the form of a cell several centimetres (some inches) long, or the egg, which is a single cell enclosed in a special medium. But in the latter case, the cell is only an ephemeral state. For as long as that state has to last the special medium contains all the reserves of raw materials that the cell needs for its development. And the seaweed? This is also no general solution of the difficulty. It compensates for its extreme length by extreme narrowness. By that means it reduces the volume-to-surface ratio. At the same time it requires only very slight exchanges with its environment. But it pays by being so eccentrically shaped.

By reason of the fact that normally shaped single cells had to remain microscopic creatures, their improvement could never compare with that feasible to metazoan forms, which were able to assemble infinitely greater stores of data.

Finally, in comparison with metazoan life, the protista, as Léon Bertin has pointed out, were like Robinson Crusoe on his island. Being obliged to be simultaneously his own carpenter, cabinet-maker, farmer, cook, tailor and so on and so forth, Crusoe was permanently tied down to life at the common-labourer level. Our metazoon, on the other hand, is able to start up industries, and the evolution of these offers him much greater scope, by reason of the endless selective research he is obliged to engage in.

So let us turn to our metazoon. At first, his shape is nearly

spherical. But he has a mouth and an anus, and he clearly moves mouth foremost. Then he grows longer in the direction of his locomotion. At the same time he increases in general size. Very soon there arises a mechanical problem: how is he to ensure the rigidity of his whole structure? So long as he was only a bundle of cells, they stuck together thanks to the forces which act on the molecular scale. There was some deformation, but not of any importance. But gradually, as the creature approached a certain size, this assemblage ceased to work. There was a risk of its deformation becoming a plaything of the outer world.

If from the point of view of pure mechanics we need to ensure the rigidity of a " parcel of organic matter ", we have two ways out. One is to enclose the stuff in a solid covering, put it in a container, in fact, the other—to build our stuff on to a solid framework. The first solution was that of the carapaceous creatures, the second that of the skeletal kinds.

To the primitive creature which had neither sort of framework, that concentration of calcareous substances to provide something solid enough to serve as foundation, whether inside the creature or outside it, was a real step forward. By these two solutions the world was provided with two great formulae, which gave birth to the orders of the invertebrates and the vertebrates.

The invertebrates mainly assumed the forms of crustaceans and arthropods. Later, some of the crustaceans took to the air and became insects. At the start, the vertebrates seemed to have chosen a thankless formula. After all, that crustacean's shell did offer some protection. It rendered the creature invulnerable to external shocks. Yet it was precisely their being open to the external world that was to permit the vertebrates to improve themselves so amazingly. For they could take advantage of the so much greater knowledge of their environment which they gained by being naked. Indeed, it was they who adopted the " correct " solution. That of the invertebrates was a blind-alley one.

III. THE INTERNAL ENVIRONMENT

External factors and mechanical considerations thus came together to suggest to the living creature a certain very general scheme of shape. Now other factors were likewise to exert an

equally dominant effect and direct the internal organisation of the living thing. Here we are thinking of the creature's own internal environment and the development of its nervous system. When we see the direction in which all these factors were acting, it becomes easy to grasp why the superior creatures were logically obliged to assume the internal anatomy which we see them possess today.

Let us, therefore, now tackle this basic problem of the internal environment, that is, the concrete form taken by *the great struggle against hazard on the internal front.* The problem had boiled down to this: how were living creatures going to create inside themselves a sort of private, internal ocean which would serve as a conditioned environmental medium far less subject to the influence of hazards than the external oceans in which they started life?

Let us go back to the case of the metazoon when this was still no more than a simple assemblage of cells. What was the most favourable shape for that little aggregate?

It is a spatial problem. For illustration, consider two armies, lined up facing one another. One takes the offensive. What does it do? It tries to encircle the other. To this end it orders its men to outflank the enemy. If possible, it deploys them in crescent formation, threatening the enemy's rear, at the same time by this trick bringing to bear on him the maximum firing power.

In other words, the logical solution for our spherical aggregate, attacking its opposing army (the fluid medium which it wishes to absorb), is to change from the purely spherical shape to that of a modified sphere—say, a football with a big dent punched into it. And this is the picture which we find in the world of living things as we pass from the simple volvox, which consists of a colony of cells in the form of a ball, to the sponge, some specimens of which are very like our illustration of the indented ball. (This, by the way, is also the first stage of the human embryo, as it develops from *morula* into *blastula.*)

With the coelenterata which follow we see the first appearance of a genuine internal environment, for in these there is a body of water retained inside the animal. This internal environment serves as a storehouse from which the living machine can get the food it requires. Access to it is controlled by the mouth. The inside of the coelenterate may thus be looked upon as a huge intestine, in which the creature stores food reserves. This liberates

it from the outer world. It possesses, so to speak, its own private ocean, of which it has complete mastery. This private ocean it can restock at will by sluices under its control which link the private store with the vast outside world of waters.

Here we have the reason for the saltness of our own blood. It is salt because it is still in this respect largely made on the pattern of the water of the oceans, of which it is a distant memory. Quinton made this cardinal observation half a century ago.

But let us now follow the living creature in its organisation from the moment when by imprisoning inside itself a certain body of water it first contrived this internal medium. In course of time ways of filtering the water were contrived, then ways of enriching it with various substances, and conveying it through pipes to irrigate all the cells of the creature.

Imagine, for instance, the coelenterata with the first internal sea. Obviously new cells are going to flourish in this sea. Eventually they form long ribbons from one side to the other. At last they almost completely fill the space. Indeed, they no longer allow it to be a space at all, or, rather, they turn it into a mass of piping, which foreshadows the network of arteries and capillary vessels of higher beings.

Nor is this all we need to notice. This new internal sea, reduced in course of time to an astounding number of rivulets, has to feed a considerable number of cells, yet it has only a rather modest volume. The debit balance must have begun to be considerable. Indeed, once this internal environment thus assumed the form of a circulatory system conveying a fluid over a closed circuit, it was bound to change its set-up along the following lines.

First, between this system of internal circulation feeding the cells and the external fluid world, some system of interchange became essential. This, however, necessitated two systems. From the outer world had to be obtained organic substances (that is to say, certain solids), and also the oxygen needed to ensure the cycle of combustion by which the cells absorbed those solids. But between these two ingredients (solids and the gas, oxygen) there was a radical disproportion. The solution of this difficulty was in the development of two distinct conduits. One opened into the mouth, the other leading to the lung, into the nostrils. The lung started with the fishes air-bladder, which in some assumed

a very large size. This was in order to offer as great as possible an exchanging surface between the internal environment and the outer one, which—life now having emerged from the waters—was the atmosphere, now enriched with oxygen by plant respiration.

The intensity of these exchanges was still further increased when the internal environment (which now we can at last definitely call blood) included elements able to fix oxygen rapidly. In the vertebrates, this work came to be accomplished by ferrous (iron) compounds. The general formula, however, was merely to enrich the fluid (the " blood ") with a suitable metal. The principal metals used are iron, copper and vanadium. Iron provides mammals with that red blood which we consider normal blood, though the iron salts which cause the redness have no other biological function than oxygen-fixing. Indeed, it is significant that the history of human blood offers us a very marked progressive degeneration. In the amphibians, the iron-vehicles were still real living cells, which multiplied in the internal fluid. With birds, a later form, the nucleus had become atrophied and incapable of self-reproduction. Finally, in mammals one can no longer speak of iron-bearing cells at all in the proper sense of the word, for in them the iron-bearing substances are no longer living; they have degenerated into mere carriers of oxygen.

Another requisite in the internal fluid was some means of destroying any alien cells which penetrated to it. This work of defence was undertaken by bodies we know as leucocytes. These cells, endowed with very pronounced amoebal tendencies, were a very early element in the blood of man. They developed particularly in the spleen, the bone marrow and the lymphatic ganglia.

To ensure circulation of the blood throughout the organism a pump now became necessary. Hence the heart. The history of this organ is most instructive. At first the closed circuit was kept in motion by a single point of impulsion. Then that point grew into a larger organ, so that the action would deal with larger quantities of blood and thereby be more efficacious. It then became S-shaped, whereby its content was increased. Then various compartments developed, linked by valves and " auricles ", all adumbrating the heart in its modern form.

Here the coelacanth has been an education in itself. The dissection of that survival fish had provided us with something

we had previously been able only to imagine, a very early model of the heart. This completely corroborated the conclusions of theory, most particularly the picture which E. S. Goodrich had already drawn to show what the heart of the first vertebrates must have been like.

This network of inner organs was finally completed in the mammals. In them, as a final step in the struggle against internal chance, heat regulation was established. The internal environment already had a constant composition. Now complex arrangements ensured that it should also have a constant temperature. In reptiles the blood temperature varies with that of the outer environment. Hence climatic and other temperature fluctuations have a tremendous effect on the internal workings of these creatures. In mammals this form of dependence on outer chance was removed. At the same time, the mammals considerably increased their lung area and stepped up their blood-pressure. In this way evolution produced a machine which not merely had constant inner environment but also great potential energy.

IV. THE NERVOUS SYSTEM

Very early on, the blood-vessels offered the living creature a "public roadway", the entry of external substances to which was strictly controlled. In this way the organism was able to use its roadway exclusively for its own substances, specially designed for its various organs. The circulatory system which thus resulted provided a network all ready to convey messages of any sort to the internal organs.

At the same time, another network was to develop, on very different lines, one of cardinal importance in the evolution of life, which was very soon also to be able to take in messages from the outer world. This was the nervous system, which was to provide the animal with a fine weapon to use *in its struggle against hazards of the outer environment.*

To analyse how the nervous system came into being, let us return once again to the most primitive forms of life, in the age in which animals were no more than indefinite assemblages of cells. Let us suppose one cell of such an assemblage to be acted on by some outside agency. For example, let us imagine it to be struck.

The blow is *a priori* going to modify the servo-cycles of the cell more or less profoundly. For a moment this ceases to show its usual physiognomy. A moment later, however, the cell next to it, hitherto in a state of equilibrium with it, will in turn be modified, and so it will go on, through the whole assemblage of cells. We may also imagine that in a few cells, at least, light will have the same effect, for it is certainly capable of producing molecular changes which will also have their repercussions on the machinery of the cell.

In primitive forms, clearly this excitation was gradually dissipated. Nevertheless, it did amount to an elementary sensation. And if this sensation was repeated, it might be "recorded" by the species just as the internal action which produces locomotion is recorded. A machinery of correlation even arose. But in any case the sensation at this level remained a diffuse one. The creature was aware of the existence of light or it felt an impact. But it clearly had no information regarding the characteristics of the light. It was not even aware of the direction from which this came, nor did it notice the object which had collided with it.

However, as the animal assumed more and more definite shape, two phenomena appeared. One was a tendency for sensory cells to become localised. Whereas at first all the surface cells were capable of sending messages to the interior, experience taught that it was those signals coming from round about the picking-up part which were the useful ones, those, that is to say, which came from near the mouth. This meant the establishment of a definite dissymmetry. The buccal region stood out as pre-eminently useful for sensory reactions. It is, for instance, significant that the olfactory organ started off as a simple sac, the wall of which was in contact with the substances newly introduced to the internal environment. These substances were, so to speak, directly *felt* as they came in, after which the cells which did this developed specially, to be better able to acquire this most useful information.

Later, when the nasal canal and the digestive tube became distinct one from another, two separate sensory organs appeared at the opening of these canals, adumbrating the mucous membranes of the nose and the tongue, and here too the cells further evolved to fit the developing function.

The appearance of the eyes near the mouth is to be explained in the same way. At first all cells were endowed with the latent power of vision. Light was originally capable of molecular action on the substance of any cell. But that latent power proved to be particularly useful for collecting information about the region into which the animal was moving, that is to say, in front of its mouth. As for hearing, here we have what in fact amounted to touch at a distance. This " formula " assumed very many different forms in the animal world. The general principle was that of acquiring information through the medium of vibrations propagated in an elastic environment. Hearing allowed an animal to obtain information on any goal before it got there, which enabled it to forestall certain events.

This fascinating grouping of sensory organs round the mouth was the starting-point for that part of the creature which we know as the head.

Development proceeds. As soon as we have sensations which are received by specialised cells, the creature's relationship to its environment is changed. This no longer acts in a diffuse way. Given these special sensory cells, we can map out " paths of maximum inclination " for the propagation of the outer excitation. Gradually, the cells along such a path underwent an evolution which in superior animals brought about a change in their fundamental nature. They ceased to multiply and turned exclusively into intermediaries. They thus formed strings of cells which transmitted electric signals by means of depolarisation taking place between each successive pair of them. This was as striking an evolution as that of the ferrous compounds which assumed the task of conveying oxygen all over the body.

Now let us turn to the centre of this network of cellular chains which began to transmit sensory messages. This became the brain. At first it was no more than the common meeting-place of all those signal paths. It became a region in which there was first exchange, then comparison of excitations. As the animal learnt by experience that from such comparison of the incoming signals he could gain the advantage of being able in advance to determine his attitude towards the outer world, that cross-roads became increasingly important. The meeting-place of tracks became a veritable marshalling yard of sensory signals. As its

traffic grew, this acquired its own signalling network, of greater and greater importance. Thus developed the brain. And just as the sensory organs were concentrated near the mouth, so too the brain followed suit and formed in the animal " head ".

Thus formed, the brain was to assume sensational development. In primitive creatures, obviously enough, it was a mere pimple. The brain of the coelacanth occupied—indeed, occupies—only a very small part of the fish's skull and weighs only three grammes. This is about fifteen-thousandths of the fish's total body weight. Even in the reptiles the brain was, and is, still insignificant and the nervous system poorly developed.

The real expansion of the brain only appeared with warm-blooded animals, that is, with mammals. From reptiles to mammals tremendous progress was made. In mammals, the average brain weight reaches about two-hundredths of the total body weight. In man, it is about one-fiftieth. Not that these proportions have any intrinsic significance. Numerous departures from any system of such ratios could be quoted. It is most mistaken to try to measure the intelligence of a creature by the weight of its brain, absolute or relative. At the same time, on the whole the systematic development of the size of the brain is characteristic of evolution.

The profound significance of the brain is in its being a sort of analogue computer. An analogue computer is one in which we achieve a true scaled-down model of the system we propose to analyse.* Today, we make use of electrical devices to work these, but there is no reason why we should not use hydraulic or any other power source. Analogue computers work in the following way. If an engineer wishes to study the possible high-water levels of a river whose tributaries have suddenly swollen alarmingly, he will set up an electric network whose characteristics will depict the whole river system. Then, having measured the rate of rise of the tributaries, he will contrive so that the current in the circuits representing each tributary expresses the rise in this, whereupon the total effect on the main river will be automatically indicated. This study of the propagation of currents in the computer's electrical system will show how the situation is likely to develop in reality. Generally speaking, the notion of an analogue

* Cf. my *Découverte de la Cybernétique.*

computer implies a correspondence between a given real system and a set of signals which are a picture of that system.*

That is just what the brain was devised to show. The work of evolution is that of continually increasing the precision of the picture. In short, the brain allows the living entity to see the outer machinery as if this were inside itself.

Here we have one of the most sensational of evolution's achievements. The living creature can use its own inner analogue computer to make estimates and on the basis of the signals coming in at any given moment work out programmes of what to do. For these incoming signals can be instantly compared with others which, previously received, have by the phenomenon which we know as memory modified the state of this. Yes, the animal calculates. We need merely to observe it watching its prey, then executing very many co-ordinated movements and leaping on the victim. The only point we must not forget is that this calculation is automatic, as automatic as is that of a slide rule, with its two parts moving one against the other and its " third part " to give the result.

Once again this cardinal warning should be made: to assess a physical situation an animal has no need to know what it is calculating. The calculation of its movements is effected in a purely mechanical way. The animal's brain works automatically without any need for " knowledge ".

The acquisition by living creatures of an analogue computer of this sort, regulating their behaviour, must have been a very great event indeed in the history of living things. It was a tremendous turning-point in the development of the power of action

* An excellent example of this use of an electronic computer is the machine which on the initiative of the Ministry of Irrigation and Hydro-electric Power of the Sudan is being built by Messrs. I.B.M., United Kingdom, Limited. It was described in *The Times* of March 22nd, 1957. The Science Correspondent of this paper wrote: " Geographically, the problem extends from Lake Victoria in Central Africa, and from Lake Tana in Abyssinia, to Aswan . . . it involves four dams already built, another eight to ten, that have been proposed or are visualised, and a 190-mile stretch of canal that has been proposed to reduce losses in the Sudd. . . . In terms of weather and water flow, the problem starts from the available records of river discharges and gauge levels during the past forty-eight years. . . . To calculate the history of Nile flows and levels, over the same period and using the same data, in any one of the many possible combinations of conditions, is several months' work for a man. The electronic computer does it in less than half an hour." (Also see Plate IV (i).)

of living things on the outer world. Now living forms possessed the faculty first of acting inside themselves on the things which surrounded them. Thus at last they engaged the future. The brain as analogue computer explains the tremendous development of the mammals. For these are creatures endowed with servo-powers infinitely more intelligently directed than the reptiles, and they are also capable of acting incomparably more simply. Thus, the instant the formula reached a stage of development at which " the critical conditions " (once again to use the language of atomic power) had been overtaken, the great hour of living things had come. The mammals were now logically bound to conquer the whole realm of the earth. The beginning of the brain was truly the " greatest ever " event in the history of life. It took place about —70 m. Then, with the appearance of creatures which could both take in signals *and see them in their own inner world*, life had assumed a totally new form.

The possibilities were now truly enormous.

CHAPTER VIII

And It Was Man

THE culmination, as we know, was the arrival of *homo sapiens*. It is with legitimate impatience and some anxiety that we reach this stage of our study. For where indeed do we fit into this picture of an utterly mechanical process? Biocybernetics has undoubtedly shown us that everything in the history of life so far was logical. The genesis and development of one species after another was all the fruit of completely automatic processes. Given mere matter at the outset, all that had been necessary was a logical process. Everything else was bound to follow.

In the light of our study, all the living species have indeed been mere machines. They were pieces of machinery capable both of self-reproduction and of taking advantage of the information which as a species they gained, using it to improve their chances of survival. Thus in the light of modern knowledge we have come back to Descartes' notorious theory: living creatures are " animal-machines ". Biocybernetics too teaches us to see mere pieces of machinery in animals. Their behaviour is determined by a number of factors, but in it there is no question of freedom of choice.

What indeed are we to conclude now that the end of our journey we reach ourselves—*homo sapiens*? For what is *homo sapiens* but the logical continuation of a genus of animals? Chapter by chapter, as the philosophical problem loomed up, this wonderful story which tells the history of living forms has been turning into the most fascinating of detective stories. And at the point we reached just before ourselves—the advent of mammals—one might have thought the dice were all thrown and that at the dénouement we had nothing left to do but to write—much against our inclination, but having no other honest course—that man too, despite appearances, was no more than another animal-machine.

No doubt he is a more perfect one. But nevertheless his freedom of choice must be a mere illusion.

However, the story of living forms is indeed rewarding. Here at the very end we find that it insists on obeying the best thriller rules. Just when all the clues do seem to have pinned down the guilty person, what do we find in the very first paragraphs of this, our last chapter, but new, sensational information which turns the story to an entirely different conclusion. For, let it be confessed at once, quite apart from any anthropomorphic promptings, we are forced to declare that, at this very eleventh hour, in man an entirely new factor, one distinctly new, does appear.

A priori, there is surely nothing surprising if this is so. We have seen before that the cumulation of a number of factors may at a given moment give rise to an entirely new function, quite different from anything which any one of those factors in itself exhibited. In the course of our survey of evolution we have examined the critical conditions which allow for the birth of new species. Here, the same process of a leap to a higher level happens again. But this time, viewed biocybernetically, the leap is of an entirely different order. We see a development which is far more important than that constituted by the appearance of the nervous system. For what happens is that man acquires a totally different sort of brain, one with which *his* kind is able—to think.

SIGHT MAKETH MAN

To understand the machinery of this last stage of evolution we need to go back in the history of living things to the point at which mammals had reached the stage of development which peopled the world with lemurs, apes and then hominoids.

Fifty years ago, after the apparent triumph of Haeckel's ideas and the discovery of pithecanthropus, the lines on which we thought were as follows: the lemur was improved till it became the ape, the ape then adopted the erect posture, and that favoured the development of the brain. That organ then increased in size, to give rise to a succession of creatures with increasing brain improvements. The last of these was man.

Today, however, we are obliged to adopt a very different account. First, nobody any longer seriously talks of being

" descended " from any such ancestry. We have already indicated how what we have throughout the history of life are differentiations. At a certain point a problem arose to which there were two solutions. One gave rise to the ape, the other to man. The differentiation between the two lines goes very far back indeed. But we also know something still more important: it is getting us no nearer a solution to our conundrum merely to talk of the volume of the brain. We need to pay our attention to its structure, the way it works.

Now, though in essence the brain was originally a marshalling yard for a developed nervous system, the information supplied to it can be made use of in very diverse ways. It is in the *method of utilisation* of the information transmitted by the senses to the brain that we should see the greatest of differentiations that the history of living things shows us. It is a differentiation the more remarkable in its not being at all spectacular. This is because basically it resides entirely in the different ways of working of an internal organ. The key difference is: thought, and the secret of the appearance of thought is to be found in: the proper use of the eye!

The point is that the early sensory organs of mammals (or preceding species) did not make it possible for the living entity to " know the outer world " in the sense in which we understand this expression, for knowing the outer world implies ability to make a fair picture of it. The animal brain works the more efficaciously in proportion to the accuracy of that picture. But such a picture cannot be acquired otherwise than through an organ which will bring the outer world to the living creature, or, more precisely, will transmit to it sufficient information for the brain to reconstitute the world.

The organs of the primitive so-called senses, touch and smell, for instance, did not really allow of such transmission. They certainly warned the animal of the existence of external objects. They even enabled it to recognise various substances, especially those which it needed for food. They were undoubtedly very sensitive senses, capable of locating things animate or inanimate at fairly large distances. They made it possible to appreciate the tracks of prey and in these ways they served the animal efficaciously. They made it possible for the animal to avoid its enemies

and find its food. But any great specialisation of the sense of smell was bound to lead to a blind alley. The development of sight, on the other hand, could make possible something very different. Among mammals note the cases of the dog and the ape.

For sight brought information which was "three-dimensional", information which made feasible a realistic reconstitution of the outer world. In this respect, the evolution of the functions of the eye is most instructive.

(1) In the elementary stage, in primitive creatures, sight was merely of the photo-electric cell order, an apparatus which noted the presence or absence of light and conveyed some notion of its intensity. In an earlier work I have studied the behaviour of an animal fitted with a photo-electric cell, for there were several primitive animals which were built on that principle.* Primitive creatures like the euglenae and the stentors therefore developed the habit of orientating to or from light.

(2) The next stage was that of an eye fitted with a number—very soon a large number—of photo-electric cells. This made it feasible to judge the direction from which the light was coming. This apparatus very quickly became generalised. We find it playing a part in the navigational methods of any animal using sunlight—and not only direct sunlight, infra-red light too. Today this ability seems astonishing to us, yet it was merely one way of using the primitive eye.

(3) There followed the first "sight of the external world". Do not let this way of formulating it deceive us. It does not follow that the possession by an animal of an eye results in its seeing the outer world as we do. Behind the eye, in the brain, we have three different parts. *First*, there is a visual area in which the messages sent by the various cells of the eye are collected. The messages come in the form of impulses astonishingly like those used in the automatic telephone. *Secondly*, there is an area of association, where these messages are analysed and combinations formed from them which enable us to identify an object from those various light messages it had sent to our eyes. And here let us not forget that the same object gives rise to different complexes of messages according to its position in front of us, according to the movements of our eye, and even according to brighter or feebler lighting.

* Cf. *L'Ere des Robots*.

Thirdly, there is finally a psychic area which works out spatial and other visual relationships and in a generalised way also furnishes the elements which are to allow us to argue about abstractions.

Such is the amazing mental organisation which we possess behind our eyes. Let us be quite clear about it: for all that it appears natural to us, it is exclusively a human feature. No other living creature possesses the psychic area of the brain. The animals' formula is limited to the visual area plus the area of association which does the analysing. But that is all, and even this latter area is as a rule poorly developed.

Could we for a moment make use of the brain of a dog or an ape, we should see the outer world in a frightfully crude fashion. For instance, when they see a brick wall, they pay practically no attention to its geometrical features. They do not even notice the regularity of the rectangles sometimes of different size, as the human mind at once does. They are merely aware of the mass of colour of the wall, its contrast, for instance, with green landscape or blue sky. This is why the drawing of a wall made by an artist on a canvas never means anything at all to an animal, which sees merely a piece of canvas stretched on wood on an easel. A typical case is that of the dog, which is unable to recognise the photograph of its master and is sometimes put out even to see (or smell) him in a new raincoat. Here too we may observe that by and large the apes are incapable too of recognising a drawing. It is only some of the higher apes which are able to see that a photograph is of their master and show pleasure at it. This is especially striking if one remembers how faithfully a photograph respects proportions and outlines, deforming or suppressing only the colours.

In any case this process of recognition depends solely on the association areas. These are clearly more developed in apes than they are in dogs. But there is no psychic area in either animal. It is manifest that any attempt to get an ape to understand a geometrical theorem is going to fail. It is only to a very limited extent that recent experiments with animals have even succeeded in getting them to grasp the appearance of a triangle and react in a given fashion when they see it.

However, although the apes and some other animals may have

an area of association which in certain cases they are able to use for mental purposes, the really great leap of evolution was the appearance of the psychic area, which achieved its organisation in *homo sapiens*. How this came about we now understand very well. New cycles of servo-mechanisms developed. When these had reached a critical point they became autonomous. We cannot do better than go back to our comparison with the atomic pile. When the factor of multiplication approaches 1, chain reactions may be set up and for a moment, locally, acquire some extent. The physicist will then speak of their being convergent, that is to say, the development cannot be maintained. When, however, the critical conditions are exceeded, the reaction becomes divergent.

It was so with the tremendous evolution which, starting from a branch of mammals, led to apes on the one hand and on the other the branch from which man has emerged. This latter differentiation took place in a very particular field by reason of the differing utilisation of visual messages by the two lines.

To the ape, walking on four legs and with a constantly moving environment before it, the essential need was factual awareness of external objects, such awareness as would ensure quick reflex actions.

The hominoid was faced with a different situation. It is far from sure that man is descended either from an ape which gave up tree climbing, or a quadruped which reared up on its hind legs. Far from this, it is quite possible that the bipedal position had been acquired long before. Comparison of the foot of man and ape scarcely suggests the derivation of one from the other. Indeed, it has even been possible to advance the thesis that it was apes which were descended from men!

What is the reasonable explanation? It is that in the hominoids a species arose which took to standing erect, on two feet. This made it more defenceless. The result was that these creatures were prompted to " reflect " on the information supplied by their vision. At the same time they were greatly aided in classifying and organising their visual data by their erect position. It provided them with a clear horizon line, a horizontal reference line to which they could refer all shapes. This gave rise to the machinery of systematic analysis of visual data. From this analysis arose the psychic area.

It amounts to this. The ape saw very many images pass before

its eye. It was able to compare them. But it was unable to organise them topologically. It was this principle of topological classification that distinguished the hominoid and resulted in the conquest of information by that species. Man was, so to speak, born a draughtsman, born with the faculty of representing the outer world and consequently of understanding it in the form of symbols, that is, by reference of the marks he made, to the real world. This gift was the very foundation of abstract thought. The paintings in the Lascaux caves are significant. They offer us a concrete example of very early art. Not that they go back so very far. They are comparatively recent, dating from only about 15,000 B.C. Prior to this the power of abstract thought and some knowledge of the mechanics of things had already enabled man to handle fire, no doubt starting from a blaze started by lightning.

Thus was completed an apparatus by which man learned to handle abstract ideas, by which, indeed, as he assembled data of the relationships which underlie all matter, he gained access to the logical laws which govern our world. This was a new start of unprecedented importance in the history of life. Let us try to see why.

THE THREE AGES OF CALCULATION

This story of life has made much use of the notion of calculation. We started by presenting evolution as the result of a tremendous work of experimental mathematics. We saw that the programme of construction of the living creature is mirrored in the genes, consequently, that heredity too is calculation.

The mathematicians have found a name for the procedure involved. They have even built machines which work by it. They call it the " Monte Carlo method ". The theory of it was mainly developed during the last war under the aegis of the American mathematician von Neumann. This mathematics is fascinating in its astounding generality, for in the Monte Carlo method there is no need to formulate equations. This means that the method is definitely indicated whenever the physicist has to admit that he does not know how to express his problem in equation form. The procedure quite simply amounts to making fictitious trials and taking the average of these.

For instance, physicists wanted to analyse the behaviour of the

neutrons in an atomic pile. They were forced to the conclusion that ordinary mathematical methods did not work. The solution was to adopt a fictitious, Monte Carlo system. A random point was assumed to constitute the possible position of a neutron in the pile. With the aid of pseudo-roulette machines, this point was now given a random direction, and random speed (the distribution of values reproducing the laws of probability). It was also given an average free passage. Further random draws were assumed to indicate the particle colliding with a neutron, the result of the impact, and so on.

In short, the Monte Carlo method consisted in "seeing" the varied fortunes of 10,000 neutrons.

Now, heredity too has faithfully used this Monte Carlo method. The only difference is that, instead of making fictitious trials, real ones were made with millions and millions of living creatures, which were all so many "guinea-pigs". It was such experimentation that automatically improved all species, for the reason that by and large it was only the more apt which survived and had descendants.

This was the first age of calculation—calculation needing neither thought nor equations, merely sufficiently numerous trials for solutions to emerge. This little game was to occupy nature for hundreds and hundreds of millions of years.

The second age of calculation came with the acquisition of a sufficiently developed nervous system. This nervous system itself was incidentally an achievement of the Monte Carlo method. It provided the living being with a genuine analogue computer. This was constituted by a brain, in which the animal could have a picture of the external world on which it could work. Nevertheless, that picture of the outer world was only a résumé of its cruder elements. Animals saw the things which surrounded them, but did not perceive their sense. We should indeed not be misled by this term "analogue computer". The engineer who uses such methods today bears in mind that his precision cannot be very great, that he will get not measurements, but merely indications. The field of application of the method is also relatively limited, for an analogue computer can never provide more than representation of a system or of a given collection of systems.

But the third stage and true age of calculation is that of numerical

calculation, which we get with *homo sapiens*. The numerical computer is a different tool altogether. It works with figures, is capable of effecting any operation whatsoever (for every operation is reducible to collections of additions). Its precision is as great as we wish. It was the property of *homo sapiens* thus to master this notion of number. Animals, naturally, perceive only quantities.* The distinction is very important.

Experiments have been reported which might lead one to believe that some animals can calculate. But they all come to nothing. When one removes the deceptive features (whether accidental or deliberate), careful analysis has always shown that animals have no notion of number.

It was the privilege of man to master the world of data. After that conquest he has with unlimited accuracy (except on the quantum scale) been able to deal with the material world. As we all know, the whole history of civilisation boils down in one way to an immense conquest of accuracy.

THE MEANING OF NEW STARTS

The fact of being obliged to take account of three very distinct ages in the history of evolution has an important consequence. It appears to be impossible to place all living things on the same curve. Or at least, this is impossible regarding each function. For instance, take the second age, that of the development of the nervous system. We can draw a curve representing the growth of intellectual level. We have referred above to André Cailleux's experimental classification. Giving the index 16 to the emergence of life from the waters, he fixed 19 as the stage of the higher reptiles, 22 as that of the birds, 26 that of the rodents, 29 that of the lower apes and 38 that of the chimpanzees.

However, things change at the end of an age, and Cailleux noted the existence of a new start at the level of 16, as if here the terrestrial environment had suddenly speeded up the mental evolution of living things. We find the same observation in Marcel Sire's work on the intelligence of animals.† Sire indicates

* Birds are, for instance, aware of small groupings, as of a clutch of eggs ,but it is doubtful if they count them.

† *L'Intelligence des Animaux.*

two such new starts, which he denotes as A and B, in the history of evolution. New start A occurs at the emergence from the waters, new start B with the appearance of the higher apes and man. It should be added that he suggested that these "discontinuities" of evolution might be illusory, and result from bad interpretation. Biocybernetics, however, teaches us that they do reflect the reality of the matter. They mark off very different stages in the general history of living things, stages with difficulty to be expressed by any common function.

Prior to Break A, only time—or the Monte Carlo method—can explain the very slow rate of evolution, stretched out over between 1,000 m. and 2,000 m. years. In that period it was hardly possible to expect learning in individuals. The living thing was no more than a machine. It lived strictly according to the programme of its birth, that is to say, essentially by instinct. Its chances of survival were proportionate to the quality of its programming. In this zone, in short, one can speak only of tropism and reflex action.

However, once we reach A, and have a nervous system, this offers the creature two ways of improving. Now, quite independently of the Monte Carlo method, the creature possesses its own analogue computer. Though at first rudimentary and imperfect, this at least does enable an element of learning in the course of each individual's life. In certain respects this liberates it from the set rules of the species. This A–B stage, marked by more and more systematic use made of the nervous system, is the stage of concrete intelligence. It furnishes remarkable performances, such as those which people like to point out in apes when these animals associate objects with movements and perform acts which are sometimes surprising, though animals only reason about physical objects.*

Finally, new start B signalises the arrival of "numerical calculation", taking the term in the sense indicated above. It is the age of logical, conceptual reasoning, such as we find in man. From the philosophical point of view this is a fact of cardinal importance. For just as concrete intelligence liberated the individual animal

* Recent experimental work in which octopuses, elephants and other animals have been trained to distinguish abstract shapes (cross, circle, etc.) merely serve to emphasise this point, for they prove that naturally animals do not perceive abstract form.

from its species, conceptual intelligence liberated it from itself. It is in this feature of man that we find free-will.

So we see that when the stage of *homo sapiens* is reached, there are in existence three systems of calculation to influence the living entity's behaviour.

First, there is the Monte Carlo method. This remains the foundation of heredity, if it is only to transmit the construction programmes for these creatures which are endowed with concrete intelligence and conceptual reasoning. This method seems to have played an important part at the dawn of humanity, when " critical conditions " were reached and the world saw the first essays made by life in the direction of *homo sapiens*. However, if we look at our civilised countries, we see that this method no longer works in practice, now that the community assumes the task of ensuring the material survival of individuals and permitting their multiplication and does so in complete independence of their qualities.

Secondly, there is concrete intelligence. This is at the foundation of our material behaviour. We have already pointed out that our brain acts as an analogue computer when we draw conclusions from concrete data. This form of calculation is accomplished without our having any awareness of dealing with numerical quantities. Nor, in fact, do we thus make use of them. Typical examples are those of the driver of a motor-car who in a flash " calculates " whether his vehicle has room to get through a gap, or the shopkeeper who with one single cut of his wire slices off exactly the right weight of cheese. Every person in his or her own walk of life in this way gets accustomed to the things he handles and acquires the ability to make rapid estimates, which are sometimes of remarkable accuracy.

But the third method, that of conceptual intelligence, is very different. Here one operates essentially with " ideas ". Everything is much more highly generalised. Whereas the concrete intelligence is able to operate only within the framework of any given organisation of the external world, this method can be used wherever we wish to reorganise that world. The animal is able only to make use of the raw materials it finds, in their natural state. Man on the contrary can shape these as he wishes and as needs arise turns them into the tools he needs. This was the beginning of the great development which I have described elsewhere, in

which man produces a new world of information which controls the material world.*

From this standpoint there is no possible comparison between the growth of servo-powers before *homo sapiens* and that subsequent to his appearance. In a very short time, there now came about a greatly accelerated transformation of the face of the earth. And the reason for this is that *homo sapiens* thinks.

To think is to understand the machinery of things. It means having in one's brain, not merely a picture of the universe, but something more useful—a systematic plan of it, by which, with simple application of the laws of logic, one can both follow and predict evolution. It means having the possibility of acting on the universe merely by manipulating symbols which stand for the world outside ourselves. To think is to have penetrated the secret of the gods, to have attained a " world of information " superior to the material world.

The material world, as we have seen, is no more than an enormous logical factory. The cumbersome, slow labour of this vast factory can now be predicted by symbols which themselves obey the laws of logic. To think is to master the abstract, that is to say, to master something which does not exist in the real world, but which is above that real world and holds it prisoner.

We may feel astonishment that after a certain stage of development evolution should thus have succeded in some measure in transcending itself. Here too let us answer the implicit question by a comparison. Take a rocket, made on our planet from matter which has never left it. We project it vertically so that it attains speeds of one, two, three and so on miles per second. Up to the speed of nearly seven miles per second, if its propellent gives out, it will always eventually fall back to the earth. But once it has attained that speed and slightly exceeded it, it will *never* come back to the earth, but will travel on indefinitely through interplanetary space. A slight increase of energy at a given point has thus made possible a complete change of state, a change of realm.

After all, this is precisely the basic notion which apparently Father Teilhard de Chardin glimpsed. Whereas men have in their time gone to enormous pains to analyse the minutest details and puzzle out complex genealogies to explain the improvement of the

* *Découverte de la Cybernétique.*

human species, the truth would appear to be fairly simple: the history of all life has been that of a continual increase in the servo-powers of living things, and this was a development which in a certain direction was at last bound suddenly to furnish life with a new realm: the realm of thought. At the same time, I suggest to the scientist of idealistic beliefs that he should now admit that phenomenogically the creation of the universe, the creation of life and finally the creation of man all derive from one sole action, namely the initial giving of an impulse which was in due course bound to lead to all these stages. Moreover, the idealistic scientist may also be duly impressed when he comes to grasp that that single initial impulse may be summed up in the four little words: " Let there be light! "

In this sense, we should not hesitate to speak of a *Kingdom of Homo Sapiens*, and, now that we have fully established this human kingdom, the classical division into the three kingdoms (animal, vegetable, mineral) should be changed in this sense. After all, this is what Blainville* suggested a century and a half ago! The gulf between the human and the animal worlds is indeed much greater than that between the animal and vegetable, where the frontier is very sketchily drawn. If we base ourselves on biocybernetic ideas, our new classification becomes very clear. The world divides into:

1. *The mineral world*, which embraces all physical-chemical phenomena, both those already studied in standard physics and chemistry and those which give rise to servo-mechanisms. The outer border of this mineral world is constituted by the molecule, which, when plunged in a suitable environment, gathers round itself elements which it finds in that medium, to make a new molecule like itself.
2. *The kingdom of life*, animal or vegetable, which begins at the point at which our molecule combines with other atoms, to form more and more complex living entities.
3. *The kingdom of man*. This appears at the point at which, the anatomical evolution being complete, the living entity begins to act on the world about it in a completely generalised manner, acquiring knowledge of the world and mastering its laws and its machinery.

* i.e., Henri Marie Ducrotry de Blainville, 1777–1850, a French comparative anatomist.

INTELLECTUAL PROGRESS AND ANATOMICAL REGRESSION

Have I really just implied that the inauguration of the kingdom of man signifies the end of anatomical evolution? Indeed I have. But why?

Quite simply, because, having conceptual intelligence, man can use this to make tools and appliances which are much more efficacious in the struggle against hazard than his own body. Agreed, the body is a piece of machinery of incredible complexity. It is capable of ensuring the most complex functions and performing a considerable number of secondary tasks, all so as to affect the outer world and combat a myriad forms of chance. But precisely because of this universality of the struggle, we must observe that, taking by itself any one of the tasks involved, a specialised tool or appliance can do the work so much better than man.

Let us be quite clear about this. It is patent that man's ultimate victory in the history of evolution has been before all else due *to his lack of specialisation*. It was his all-roundedness which made it feasible for him to get on top of the world. It also enabled him to correlate the results of very diverse acts. In distinction from all-roundedness, specialisation always leads living things into blind alleys.

But now, the moment that man can make artificial devices external to himself which prolong his existence, he combines both the advantages of non-specialisation and those of specialisation too. From this point on, evolution uses man *as a brain* utilising a huge number of specialised machine-tools to do things for him.

The fact that all his tools manage man's struggle against hazard for him relieves his body of the effort, to such an extent that, taking all in all, we cannot but speak of a formal regression of that body. Since this no longer has to call on all its powers, there is every likelihood of various of its functions atrophying. Indeed, have we not already the first hints of this, in the de-animalisation of the human face which began to develop when the mouth was no longer needed for grasping, that function being taken over by the hands, once the biped began to convey its food to its mouth with them? As gradually man has come to replace by artificial means the mechanisms of muscular action which his body

was formerly forced to devise, this tendency towards regression must have become a generalised one.

We see it quite plainly enough in our civilised world. It shows up in a variety of ways. Man of today has grown accustomed to living in comfortable dwellings, in which the struggle against hazard is ensured by a great variety of devices, which protect him against bad weather. He has constant indoor temperatures, he has scientific preparation of food of well-planned composition, he has his foam-rubber beds, his lifts and all his other gadgetry aimed at reducing effort. Just think what would happen to us were we suddenly to be cast back about 100,000 years and, subject at the same time to the attacks of wild animals, obliged to do without beds, without houses, almost without clothing! Compare childbirth then and now. Need more be said?

In short, the tools which man has created have brought him to an anatomical regression. *A priori* there is nothing bad in this, in so far as the future of the species is not thereby threatened. Nevertheless, we must not close our eyes to a certain danger of such a threat appearing, with the way progress is developing at present. Any culture or race which, exploiting the situation, now aimed at luxury for luxury's sake, with the elimination of all effort for the individual, bringing up its children "in cotton wool", would certainly be mortgaging its future rashly. It would risk losing all the acquisitions of biological development and condemn itself to an ever more complex artificial environment, the stability of which is quite unproved.

To come back to our primitive man, is it quite clear what we mean when we say that with him evolution was completed and initial *homo sapiens* constituted a real anatomical peak? Examine the remains of Cro-Magnon man or a description of him! He was a truly magnificent creature, very big—average height six feet—with imposing square shoulders and outstanding physical resistance.

THE TRIUMPH OF THE MIND

It was this primitive man, endowed at last with the conceptual mind, capable of grasping the logic of things, who was to start organising the world after his fashion, and first and foremost, to a

remarkable degree, by artificial means to begin to turn the struggle against chance to his own profit.

Thus in the conditions of life on earth was to begin a tremendous change which we may sum up as: *complete conquest of the biosphere by man*. Once man was able to act at will against chance, the biological realm of the individual, which I have tried to define in the preceding chapter, was to expand till it embraced all the realms of all other forms of life. From then on man imposed his law on almost all the rest of the living world. For we must note two interesting exceptions—insects, and also the world of very small things, which, quite apart from their ease of movement, due to almost complete lack of inertia, tend to escape man's notice.

In brief, the world of living things was to change radically and the earth was to be transformed. For now that man understands the way nature works, is not everything materially possible to him?

The transformation began with primitive humanity itself. Though man had certainly acquired conceptual intelligence, the practical application of this was to call for a tremendous labour. It is not sufficient merely to " have a notion ". To put the notion into effect a tremendous work is required. Think merely of any new mechanical device, and all you would need to realise it satisfactorily. Nor should you forget that today you have very many powerful tools at your disposal and can also have other people to help. Primitive man had nothing of that. His only tools were the things he could find round about him, sticks and stones and bones, which his hands could shape painfully, after which he might use those first tools to fashion others.

Besides, in those very early days, man was before all else the prey of the large predatory animals. Let us not forget that up to fairly recent times this continent of ours was still peopled with bison, reindeer, mammoths, hairy rhinoceroses, the latter ominous beasts as big as our elephants. Practically, when up against them, man had only one policy: flight. He profited by his agility to avoid his enemies. Next, he prepared traps and made his home up cliffs in caves which the animals could not reach. It is significant that Périgueux, which offers such conditions, happens to be a sanctuary where we have found so many homes of primitive mankind. For some time in this early stage man's policy was a defensive one. The earth still did not belong to him.

The situation was not to be reversed till the end of a long struggle. Gradually, however, *homo sapiens* won ground, thanks to increasingly powerful weapons. He made tools which were more and more effective. He established himself in entrenched camps, in which the first industries had their birth. Dressmaking and tailoring, for instance, started at a very early period. Next, leather buckets were made. These made the birth of the kitchen feasible. Better weapons were made. Soon, the struggle was organised on a grand scale. Man began to hunt. At last he attacked the most menacing of the animals, mastering them with weapons and traps. We have had numerous descriptions of these events. For instance, man made a circular enclosure, walled with rocks, with an entrance through a corridor, on the very plan used for the wild animals in present-day circuses. The outer end of the corridor was wide-mouthed, opening on to a track down which the animals could be driven by beaters. Imprisoned in the stockade or walled arena, the dangerous bisons were killed with lances which the men could throw in from outside.

Thus man exterminated or chased away the animals which he feared. At the same time his corralling technique furnished him with the beginnings of stock-raising. Instead of killing all the captured animals at once, he realised that it would be wiser to let some of them live, killing them only when he needed them. Once man thus kept stock in an enclosure, where it could not harm him, but would at the same time go on feeding and multiplying, he had freed himself of the perpetual need to hunt for his maintenance.

It was only between 10,000 and 5,000 B.C., that in a general sense this struggle for mastery of the earth, the first act in man's conquest of the biosphere, reached its completion—at least in certain regions. It was now that there began man's grand expansion over the world's surface. At the same time as he evolved stock-raising man also invented agriculture, with striking consequences.

The first result of agriculture and stock-raising was the acquisition of a much better food supply than could be obtained when man lived solely by the hunt. As at the same time the menace of the wild decreased, the new techniques gave rise to a tremendous spread of population. A great process had begun which was

finally to result in man's penetration to all parts of the world. Whereas primitive humanity seems to have been confined roughly to a T-shaped zone, the horizontal crossbar running from France to Java, and the upright from the Middle East to South Africa, the conquest of the whole world was suddenly to become a reality. Man now spread from Asia into the Americas. The human population began to increase exponentially, till the human race was to be counted in millions, then in tens and eventually hundreds of millions.

Further, with the establishment of stable sources of food, by stock-raising and agriculture, populations became sedentary. The first established communities appeared. The fertile valleys and plains became a territory which could no longer be abandoned, but must be defended against natural afflictions and also the covetousness of other men. Hereby the struggle against hazard changed its form. Man had moved chance one stage farther from himself. He disposed of food supplies, but he still had to control other factors which might deprive him of those supplies.

This meant that the first human societies suffered various fates according to whether their agriculture and stock-raising were able or not to assure them abundance of regular food and the hazards were still to be overcome. In the rich valleys the struggle was easiest, minimal. Thus, in Mesopotamia and on the banks of the Yangtze in China and the Nile in Ancient Egypt, the world saw the first civilisations, the first stable settled cultures, lasting for some 3,000 years, with a remarkably high degree of human survival.

These, however, were still exceptional cases. If we look at the general history of humanity, we see the peoples of the world much preoccupied with the struggle against hazard, waging it with whatever means their circumstances offer them. The activity and the soul of every people is dominated in the last resort by this struggle. But across our standard histories there is now another great history to be written, the story of that continuation of the great fight against chance which is the very essence of life, now that it is waged with thought. It becomes fascinating to see how people wage it in one epoch or another, under one set of circumstances or another. Here, cold was the main enemy, there, wind and rain. Here transport was difficult, there one had an island easy to defend. Every country, every region, every culture has had

its own features, its own developments, its own aims, suggesting to man fresh ideas about the organisation of his communities.

This is the sensational next instalment in the history of life. Given the formation of beings ever more apt to ensure the reproduction of their germ-plasm, with man we have this problem of the conscious struggle against chance. Man literally emerges from his own body to project himself farther and farther out over the outer world about him.

BUILDING THE WORLD OF INFORMATION

This, however, has all been merely the prologue.

Having cleared the face of the world of whatever was a hindrance to him, man set about making a methodical examination of his planet. Taking his own country as triangulation base, he applied his thought to the task of relating everything to it. In short, he laid the foundations of what was to be the great edifice of science. His foundation took the form of a world of information symbolising the outer world by an agreed code. Man wished to elucidate the general laws by which through signs he could reason about a world of data symbolising abstractions. As we have remarked, the essential property of the conceptual intelligence was the comprehension of the machinery by which the world works.

The first part of this work was thus that of perfecting the key tool of the intellect by elaborating a system of writing to enable him to communicate his thought. A first step was made of course long ago, with spoken language. At a very early stage man began to utter cries to express his thought. We can see signs of the rudiments of articulated language in the structure of the jaw of *pithecanthropus*, Mousterian man, in the Old Stone Age, though at this stage the jaw was too narrow to have allowed for easy articulation. Speech was born with the very first exchange of information. That is to say, it was an action concentrated in groups of men. Unfortunately, spoken words are fugitive. They do not carry far. Their usefulness is essentially limited to momentary effects.

The real build-up of knowledge was, however, not to begin properly till writing was invented. The great feature of writing, which distinguishes it from direct oral communication, is that it

sets the information down for use at some later time. Hence it furnishes the brain with registers, in which man can keep a record of the past, to examine later and compare with his subsequent experience.

Writing was born of drawing. Though a number of peoples were to stick to concrete picture writing (the case of Chinese is outstanding), it became clear that time was to be gained if the drawings were stylised and then further reduced to a small number used not to indicate concepts at all, but the sounds which make up words. From ideograms were taken signs which, reshaped, were to give rise to our own alphabet and also to stand for numbers. It was achieved by selecting twenty-two hieroglyphs for the twenty-two consonantal sounds of early Hebrew.* We do not know the name of the man who first took the step of establishing the great invention of phonetic writing, capital though it was for all the subsequent intellectual evolution of humanity. Was Moses the great inventor?

Then came the "Greek miracle". In a kindly Mediterranean climate, an astonishing civilisation was born, to produce a highly organised society, the thought of which was expressed by men whose names still have great prestige. The Greeks pushed the theoretical study of logic in all forms to a very high point. This included the development of mathematics. They developed this science as far as the calculation of the arc of the cycloid. They also achieved technical wonders in the form of a variety of machines. Indeed, one has to wonder why the world had to wait 2,000 years more for the industrial revolution to introduce systematic servo-control of the material world. But the Greeks failed to invent printing. Consequently, they had no means of systematically publishing their information. More decisive still, they were only a striking exception in their age. Consequently, before their thought could master the material world, they were submerged.

That mastery of the world which—on this point we can never insist too much—was fated from the very outset, being but the logical consequence of the appearance of thought, was not to

* Originally, Hebrew did not write the vowels, but a sort of shorthand, with consonants only. This is to be explained by the nature of Hebrew words, which are all most logically formed from a basis of three consonants (except for a few cases of two consonants, usually resulting from the coalescence of two of the original three).

come till the nineteenth century. It is only then that the world saw any systematic application of thought. But once man had begun to run up the scaffolding of the edifice of science which established a fairly close correlation with the real world, he had two possibilities before him. He could construct tools which would provide him with more and more information about the real world, and he had at the same time the possibility of making machines do for him all those controlled tasks which only yesterday he had confided to slaves.

In 1800 began the exploitation of artificial power sources to replace human muscle. With this step came an astonishing extension of the field of action of machines. This, however, was still only a partial solution of man's problem, for every controlled machine act still required the co-operation of eyes, muscles and brain. The real industrial solution was only to come when a complete system of controlled action by machines had been evolved. Such machines we commonly know today as robots. Their essential feature is that they are fitted with receptive devices which play the part of sensory organs and have more or less complex devices for discriminating, so that they automatically extract guidance from the information their receptive devices obtain, and use this to work their motive units.

From this standpoint it is thus only today that the real battle for man's conquest of his living space has been engaged. The suggestion that we are just beginning to go through this stage, of such cardinal importance, may seem a sort of self-centredness. Nevertheless, I am sure that is the position. It is now that the phenomenon of *homo sapiens* is beginning to appear in all fullness.

This total industrial revolution through the birth throes of which we are now passing does indeed promise us something man had never envisaged before: the possibility of a mechanical world taking over for us our struggle against chance and doing this as completely as we may desire. I say " taking over the struggle for us ", but of course I do not mean without supervision. After all, the robot does no more than synthesise into actions whatever instructions about this we give it. Yet robots can go a long way. It is today even possible to go so far as to conceive of robots which will perform a plurality of controlled actions and also be capable of learning. But even so it is surely clear that it would be impossible

for a " race " of robots to " live " by themselves on our earth, for the simple reason that it is inconceivable for a robot to have the power of seeing the outer world which our eye possesses, let alone accomplishing the sort of work which the thinking areas of our brains do.

All that is now required of man is to maintain a less and less important supervision of a more and more far-reaching programme. For tomorrow our industry will be organised on an entirely new foundation. It is putting it mildly to remark that so far our industries have been built up haphazard as possibilities presented themselves with ruthless exploitation of our mineral resources. It was our fortunate access to these that enabled us to start up industry at all. But we should do well to note that the coal and iron we have drawn on so lavishly were essentially products of life. Yes, even the deposits of iron are the work of the bacteria whose patient labours over many early millions of years we have noted. Other bacteria concentrated manganese. Cormorants and other birds of that sort excreted the guano, which, oxydised, constitutes the famous saltpetre deposits of Chile. The phosphates of North Africa owe their origin to the fishes of the Tertiary epoch. The large part of our deposits of coal derive from the remains of the abundant vegetation of the Carboniferous epoch, while our petroleum comes from the decomposition of the corpses of secondary animals of the Secondary Era.

All our mining operations together, utilising these resources, have been most valuable for feeding our machines. But they will only last a certain time. The supplies of some of the raw materials which they provide will soon run out. Figures of less than fifty years are frequently quoted for copper, lead, zinc, nickel and petroleum.

Thus in the framework of the world automation which should now be our main goal the industrial problem will have to be tackled in a very different spirit. The essential thing will be to find an automatic source of energy. The arduous work of extracting and transporting our minerals may well be abandoned, to give place to the direct seizure of solar energy and the erection of nuclear power stations. These, established beside the seas, would be able to provide energy indefinitely. Coal could then be more and more reserved for the manufacture of plastics, which will

assume ever greater importance as we enter the twilight of the age of metals. The metals which today are in common use will in time become very rare indeed. They will then have to be reserved for special uses. For instance, electronics will one day absorb all the copper available.

At the end of world automation, the aim of industry should at last be to relieve man of all material preoccupations about his own maintenance, or at least to ensure his supervision of these functions being reduced to a secondary task. Only then, under the sign of a grand age of the intellect, rising far above our past and our present, will there at last be reached that total victory of thought which it is man's mission to achieve. There will then follow the marvellous conquest of the other heavenly bodies, and the reign of human thought over ever vaster regions of the vast universe.

Yes, and that will be because it is logical that it should be. In this great chain of logical development, the miracle of man has scarcely begun. Thought is eventually bound to take us very far, into very exalted realms, where perhaps we are expected.